

# A new class of phosphine ligand for asymmetric synthesis

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*Award date:*
1995

*Awarding institution:*
University of Bath

# A New Class of Phosphine Ligand for Asymmetric Synthesis

Submitted by Guy Brenchley
for the degree of PhD
of the University of Bath
1995





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# Abbreviations

**Chemical Groups:**

Ac - acetyl

Bn - benzyl

nBu - butyl

$^{t}$Bu - *Tert*-butyl

Cp - cyclopentadieneyl

Cy - cyclohexyl

Et - ethyl

Me - methyl

Ph - phenyl

**Solvents:**

DCM - dichloromethane

DMF - dimethyl formamide

EtOAc - ethyl acetate

THF - tetrahydrofuran

IPA - propan-2-ol

**Reagents:**

BSA - bis(trimethylsilyl)acetamide

DPPA - diphenylphosphoryl azide

TBAF - tetrabutylammonium fluoride

TMEDA - tetramethylethylenediamine

**Bases:**

DABCO - 1,4-diazabicyclo[2,2,2]octane

DBU - 1,8-diazabicyclo[5,4,0]undec-7-ene

nBuLi - *n*-butyllithium

*t*BuLi - *Tert*-butyllithium

**NMR spectroscopy:**

| | |
|---|---|
| $^{1}H$ - proton | $^{13}C$ - carbon |
| $^{31}P$ - phosphorus | $^{11}B$ - boron |
| J - coupling constant | |
| s - singlet | d - doublet |
| t - triplet | q - quartet |
| p - pentet | sex - sextet |
| m - multiplet | br - broad |

**General:**

| | |
|---|---|
| COD - cycloocta-1,5-diene | ee - enantiomeric excess |
| HPLC - high pressure liquid chromatography | |
| MPV - Meerwein-Ponndorf-Verley | RT - room temperature |
| TBDPS - *Tert*-butyldiphenylsilyl | TBS - *Tert*-butyldimethylsilyl |

# Acknowledgments

Many people have helped me in this project. I would like to thank a few from Bath University; Professor Malcolm Sainsbury for sharing his experience, Dr Dave Brown for his practical advice and encouragement, Dr Ali Ninan for her interest, Dr Richard Kinsman for his NMR expertise and good cheer and Dr Mary Mahon for her directness.

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Thanks must also go to my fellow students and post-docs; Dr Barry Burns, Doug Critcher, Matt Fletcher, Anne Hackett, Wilson Leung, Dr Eric Merifield, Matt Palmer, John Studley and Heather Tye amongst others. The atmosphere of a lab. is *definitely* the sum of the people that work in it.

Finally I must thank my academic supervisor Dr Martin Wills, without whom this project could not have existed.

# Summary

This project describes the rational design, synthesis and screening of several phosphine ligands containing the dihydrobenzazaphosphole-borane moiety.

During initial synthetic studies *ortho*-lithiation methodology in N,N,N'-benzyl-trisubstituted ethylenediamine type systems was examined. Once *ortho*-lithiation methodology had been optimised, trapping the *ortho*-anion produced with a P(III) electrophile and protecting the generated P(III) centre with borane was examined.

Existing deboration methodology was applied to the compound produced to give a P(III) / nitrogen bidentate ligand. This ligand was applied to the Pd catalysed allylic alkylation reaction giving reasonable enantiocontrol.

Examination of the reaction mechanism suggested that a synthetically simpler monodentate P(III) ligand may be of interest. Using previously described methodology an N-silyl dihydrobenzazaphosphole-borane complex was synthesised. Deboration of this compound gave an unusually effective ligand for the Pd catalysed allylic alkylation reaction giving very good enantiocontrol.

Further studies into alternative syntheses of the dihydrobenzazaphosphole core led to the development of a halogen-lithium exchange reaction with wide applicability to synthesis of unsymmetrical diphosphine ligands. A $C_2$ symmetric diphosphine-diborane complex was synthesised using this methodology and the use of its deborated relative in Rh(I) catalysed hydrogenation of an N-acyl-(α)-aminoacrylate, Rh(I) catalysed hydrosilylation of acetophenone derivatives, and a Pd catalysed asymmetric variant on the Heck reaction are examined.

Possible future work using this methodology is described.

**To my parents and family for support and encouragement**

**To Slyv for support, encouragement and putting up with me!**

# Index

# 1. Introduction

## 1.1 - The importance of chirality:

Chirality is fundamental to life. The majority of amino acids are chiral, as are saccharides, steroids, many terpenes and DNA itself. Organic, and in particular, medicinal organic chemists have long been trying to perturb the biological system in a controlled manner using synthetic compounds. Chirality in synthetic compounds introduced into the biological system can have dramatic effects and this in turn means that control of this chirality assumes vast importance.

## 1.2 - Sources of chirality:

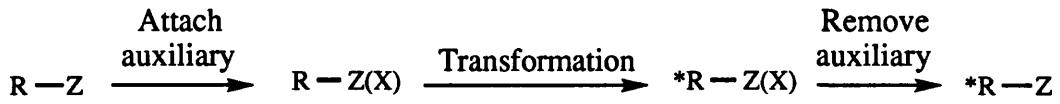
There are four main sources of chirality:

a. The chiral pool: Naturally occurring non-racemic chiral compounds such as amino-acids can be synthetically elaborated to give homochiral targets. The limited range of starting materials often leads to a long, complex and inefficient synthesis. Also a large number of the members of the chiral pool only occur naturally in one enantiomeric form, thus necessitating clean inversion if the other enantiomer is required.

b. Resolution: If the target compound contains certain types of functionality it is often possible to resolve the enantiomers at a racemic chiral centre using material from the chiral pool. Unless the unwanted enantiomer is easily racemised the maximum possible yield is only 50%.

c. Stoicheiometric asymmetric synthesis: If an auxiliary containing one, or more, defined chiral centre(s) is attached to a substrate prior to reaction (see Scheme 1.2.c) diastereomeric transition states for the reaction are possible. Each of these diastereomeric transition states has a different energy and thus it is possible to bias the formation of one possible enantiomer over another by careful selection of reagents and auxiliary.

Scheme 1.2.c

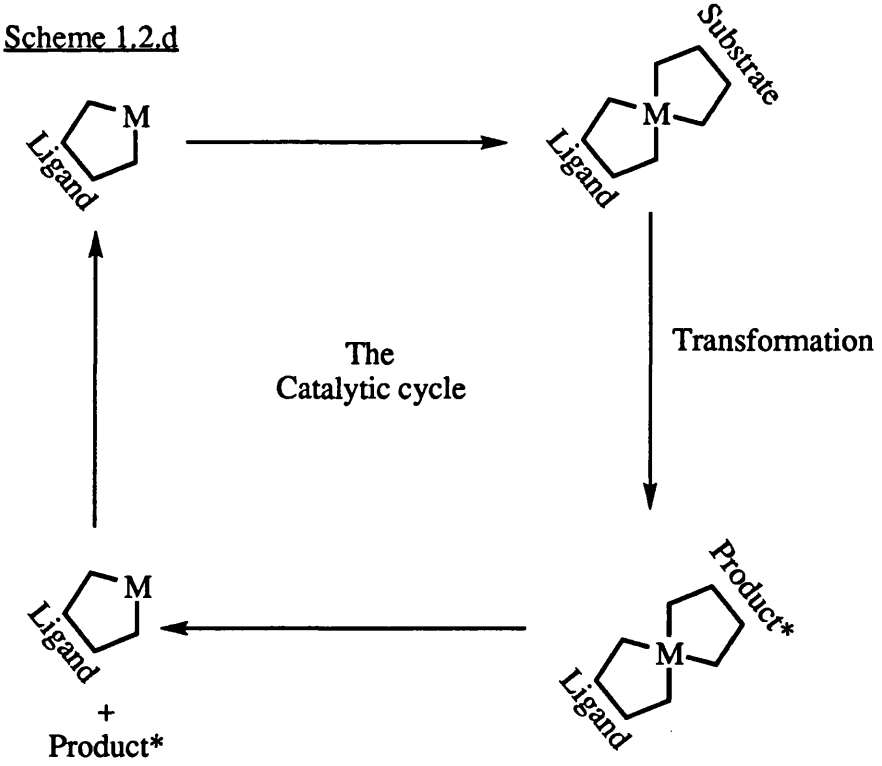



R = substrate, *R = chiral product, (X) = chiral auxiliary, Z = reactive functionality

Although much work has been done on this methodology[1] there remains the problems associated with attaching, removing and recovering the auxiliary.

d. Catalytic asymmetric synthesis; In principle, synthetic chemistry can create any chemical function at will and catalysis, unlike ordinary stoicheiometric synthesis, is capable of multiplying chirality. In a catalytic asymmetric reaction the chiral environment necessary for enantioinduction is provided by one or more chiral ligands. These ligands coordinate to a metal centre, usually a transition metal, around which the transformation takes place (see Scheme 1.2.d).

Scheme 1.2.d



The first reported case of asymmetric catalysis came in 1966 when the decomposition of ethyl diazoacetate in styrene was catalysed smoothly by a small amount of Cu(II) / chiral Schiff base complex, leading to *cis*- and *trans*-2-phenylcyclopropane carboxylic esters in < 10% ee.[2]

Catalytic asymmetric synthesis has the major advantage over stoicheiometric asymmetric synthesis that very small amounts of chiral ligand are used relative to substrate, giving high chirality multiplication. This makes it cost effective to synthesise complex ligands for very specific applications maximising yield and enantioselectivity.

1.3 - Ligand development:

Since 1966 massive research efforts have given several generations of ligands as current thinking has been altered by various empirical results. Using asymmetric hydrogenation as an example gives a good illustration.

The use of Wilkinson's catalyst[3], **1** (Figure 1.3.a), showed that Rh(I) salts complexed to phosphines were extremely active homogeneous hydrogenation catalysts. Replacing the triphenylphosphine in Wilkinson's catalyst with a phosphine, **2**[4], chiral at phosphorus, gave an enantioinduction but further reduction in the number of degrees of freedom of the ligand were needed to give a high selectivity. This led to the use of chelating diphosphine ligands, **3-8**[5], giving a five- or seven-membered ring when attached to the Rh(I) centre. Initially, chirality at phosphorus was deemed important but the discovery of DIOP, **4**, proved this to be wrong.

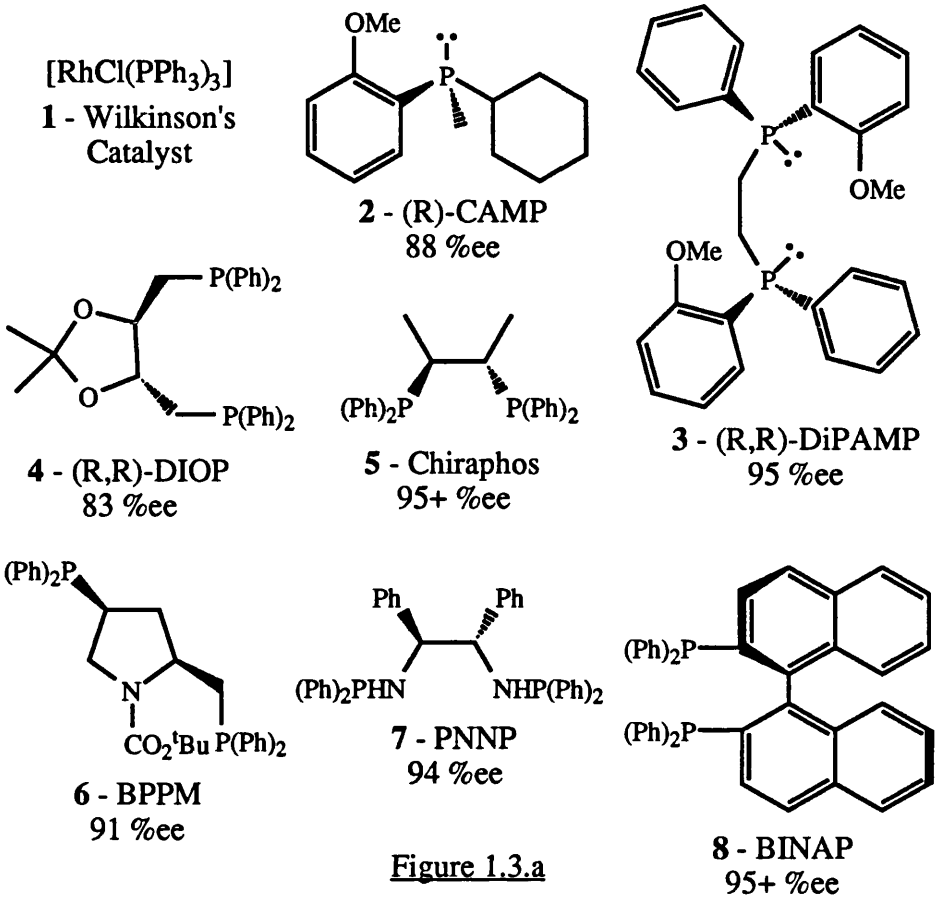
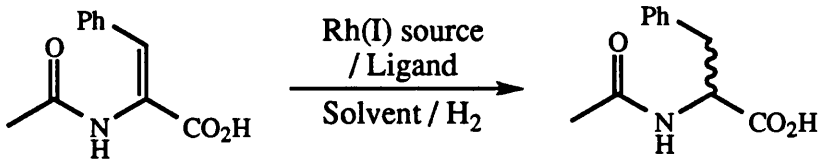


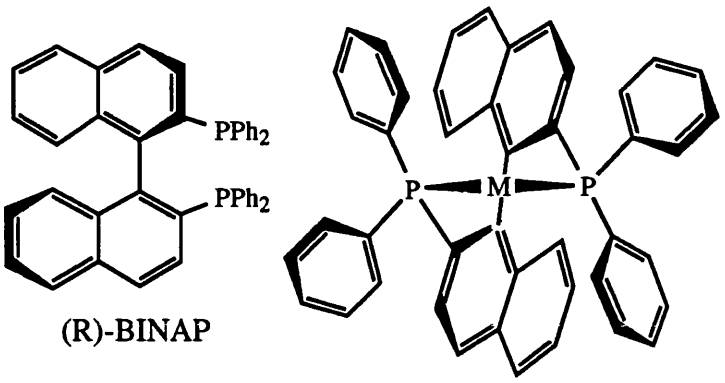

Figure 1.3.a

Using the reaction shown in Scheme 1.3.b as a screen, each of the ligands in Figure 1.3.a can be compared. Enantiomeric excesses obtained in this reaction are shown.




Scheme 1.3.b

A very important feature of all of these ligands shown in Figure 1.3.a, except **2**, is that they give a 'propeller' array of phenyl rings when placed around a metal centre (see Figure 1.3.c).




(R)-BINAP

BINAP / M complex

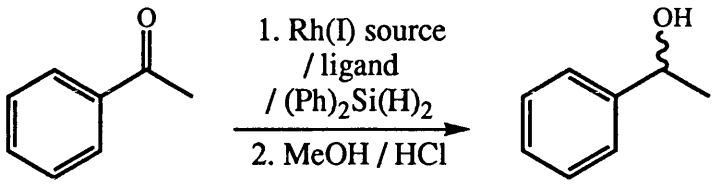
Figure 1.3.c

It is believed to be this highly chiral environment which leads to the inductions observed.

In principle virtually any atom with an available lone-pair of electrons could be used to bind a chiral ligand to a metal centre. However, certain metals will bind strongly to one type of ligand over another[6] thus allowing the development of ligands for specific metal / reaction combinations. Conversely, it has been found that phosphorus in the P(III) oxidation state binds reasonably strongly to a wide range of metals[7], thus making phosphine ligands particularly general and hence particularly attractive. Although each of the above ligands were originally developed for hydrogenation many have been found to be useful in a wide range of catalytic asymmetric processes. A closer look at three such reactions will give a basis for later chapters.

1.4 Other catalytic reactions:

a. Hydrosilylation; Reduction of a carbonyl group by a silane can be enantioselectively catalysed by Rh(I) complexes (see Scheme 1.4.a.1).




Scheme 1.4.a.1

Although there are many ways of reducing a carbonyl group with high enantioselectivity[8], only catalytic hydrogenation[9], the modified Meerwein-Ponndorf-Verley reaction[10] and hydrosilylation[11] use a ligand-metal type catalytic cycle.

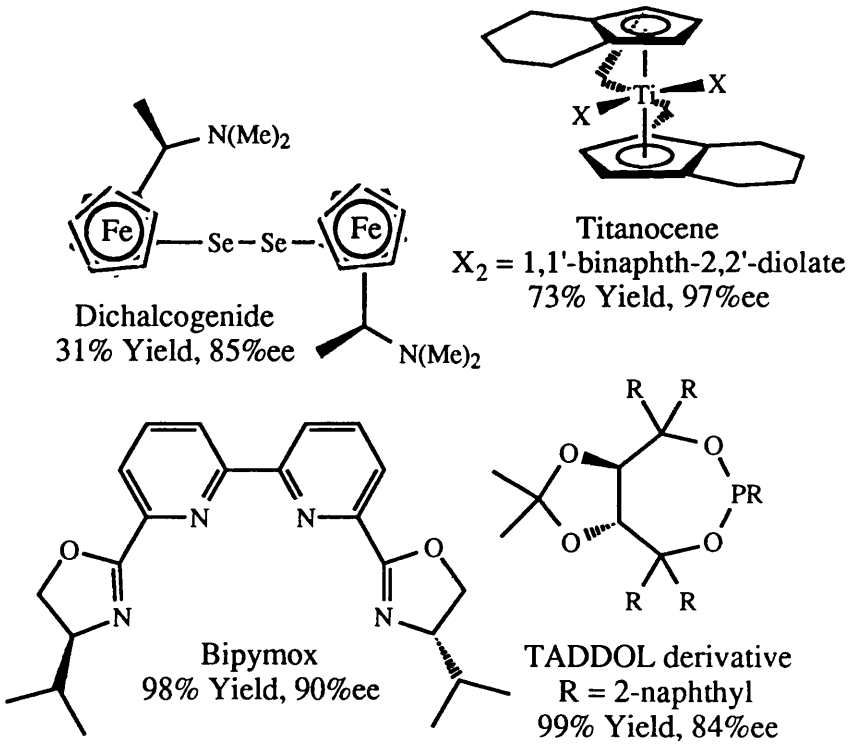
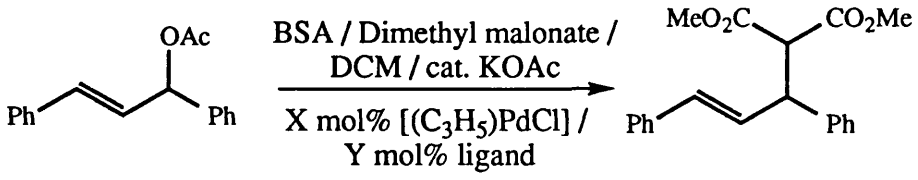



Figure 1.4.a.2

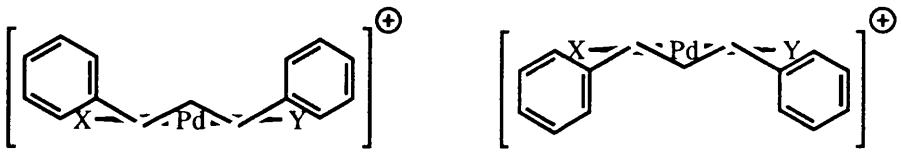
From Figure 1.4.a.2 it can be seen that widely differing types of ligand have been used[11], each having a different substrate range and activity. Enantiomeric excesses and yields refer to these ligands being used in the reaction shown in Scheme 1.4.a.1. All of these ligands provides a chiral environment around the Rh(I) centre to which the ketone binds. One face of the ketone is then favoured over the other when the silane adds across the C=O bond. A methanolic solution of HCl is then used to cleave the Si-O bond releasing an enantiomerically enriched alcohol.

b. Allylic alkylation; There has been much recent interest in this reaction[12a,b,c,d] and several interesting and instructive points about ligand design have been highlighted by these research efforts.




Scheme 1.4.b.1

When a Pd(0) complex with two labile ligands is exposed to an allylic acetate a Pd π-allyl species is formed, Figure 1.4.b.2. This is the reactive intermediate in the reaction shown in Scheme 1.4.b.1.




'W' geometrical isomer 'M' geometrical isomer

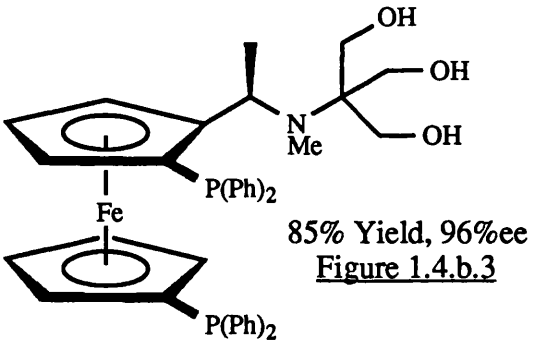
X, Y = Ligands

Figure 1.4.b.2

There are two main problems when trying to obtain enantioselective addition to a symmetrical allyl complex. The first involves influencing which geometrical isomer predominates ('W' or 'M' complex, see Figure 1.4.b.2). The second involves controlling which end of the symmetrical allyl system is attacked by an incoming nucleophile. Both of these problems have to be addressed to obtain an enantioinduction.

It is known that ligands in square planar Pd(0) complexes are located on the side of the allylic group *opposite* that of nucleophilic addition. This makes ligands that operate in a purely steric manner less effective than expected. Indeed, **4**[13] and **8**[14] have been used in this reaction and gave relatively poor results. Thus, if a ligand is to influence which end of the allyl group is attacked by the nucleophile, it must use one or more, other means of control.

There have been three main approaches to this problem. The first was to use a long tether that interacts with the incoming nucleophile *on the opposite side of the π-allyl Pd complex* and guide it to one terminus of the allyl system.[15] Figure 1.4.b.3 shows one such ligand and the yield and enantiomeric excess obtained when it is used in the reaction shown in Scheme 1.4.b.1.




85% Yield, 96%ee

Figure 1.4.b.3

The second approach uses steric bias in a different manner to that usually encountered. By introducing steric clashes between the ligand and the allyl system one of the Pd-C bonds can be selectively lengthened. The sterically strained terminus of the allyl system is more electrophilic and thus is preferentially attacked giving an

enantioinduction. Aza-semicorrines[16] and bis(oxazolines)[17] , see Figure 1.4.b.4, have both been used extremely effectively in this manner. The yields and enantiomeric excesses quoted are those obtained when these ligands are used in the reaction shown in Scheme 1.4.b.1.

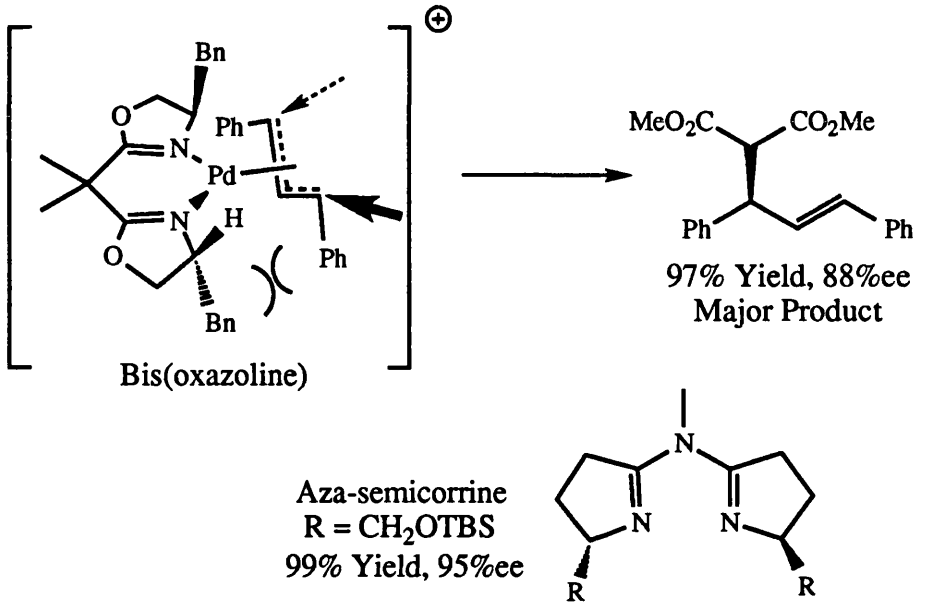



Figure 1.4.b.4

The third method involves using electronically different coordinating atoms in a bidentate chelating ligand. The ligand thus influences the positive charge density at each end of the allyl system in a different manner, increasing the electrophilicity of one end over the other, causing desymmetrisation.

The charge density at each end of the π-system is influenced by the ligand atom *trans* to it in the complex. P(III) centres are good π-acceptors[18] and thus increase the positive charge density *trans* to themselves in the complex. First period elements such as nitrogen do not have this π-acceptor ability.

The groups of Williams, Pfaltz and Helmchen have all published extensively in this area elucidating some very unexpected results. When the ligand **9** (Figure 1.4.b.5) is

used in the reaction shown in Scheme 1.4.b.1 superb results are obtained (99% yield and 99%ee), but the product is of the *opposite* configuration to that intuitively predicted (Figure 1.4.b.6). Either the nucleophile is attacking the allyl terminus opposite the nitrogen donor atom or the sterically congested 'W' complex shown in Figure 1.4.b.6 is the intermediate in this reaction. It has been postulated that the (α)-H next to the phenyl group on the oxazoline is the controlling steric factor. The interaction of this proton with the allyl phenyl group makes the 'M' configuration complex disfavoured.

Extensive NMR and X-ray crystallographic studies on π-allyl Pd complexes of phosphinoaryloxazoline ligands[19] showed that the 'W' complex shown in Figure 1.4.b.6 *is* the major component in the solution and solid phase. In the 'W' configuration complex there is still a severe steric interaction between the oxazoline substituent and the adjacent allyl group and this distorts the square planar geometry around Pd such that the Pd-C bond *trans* to P is longer, and thus weaker, than that *trans* to N. It is therefore the combination of steric *and* electronic factors that makes this class of ligand so effective in this reaction.

**9**

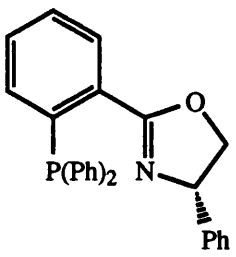



Figure 1.4.b.5

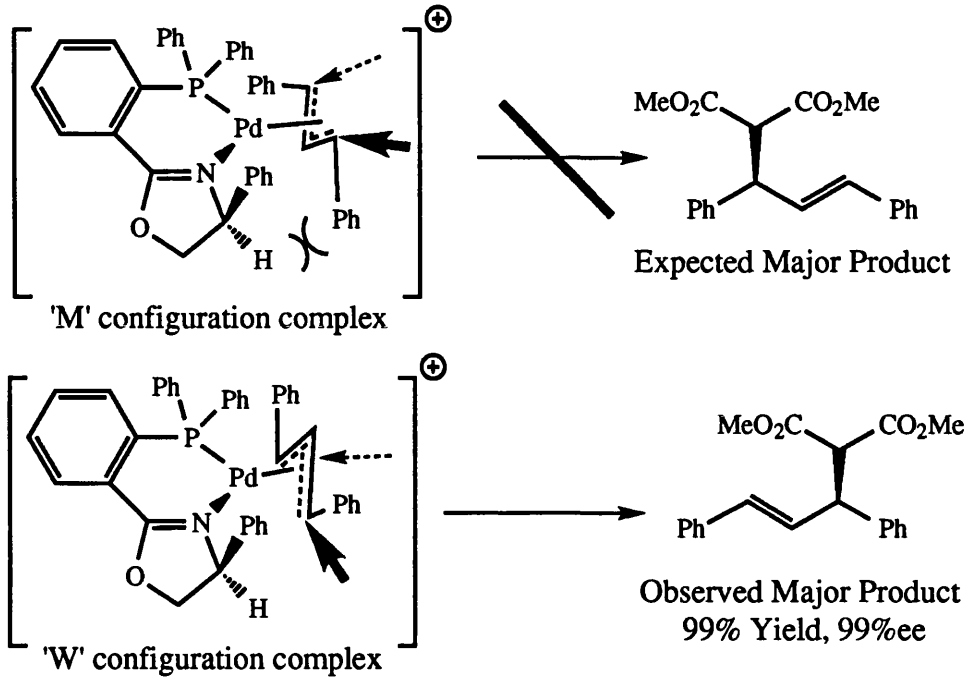
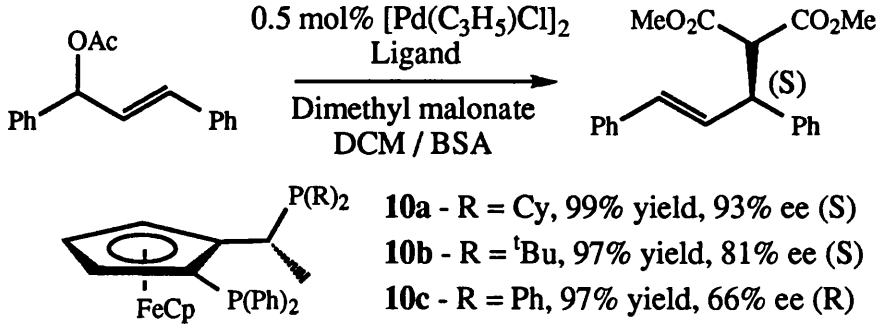



Figure 1.4.b.6

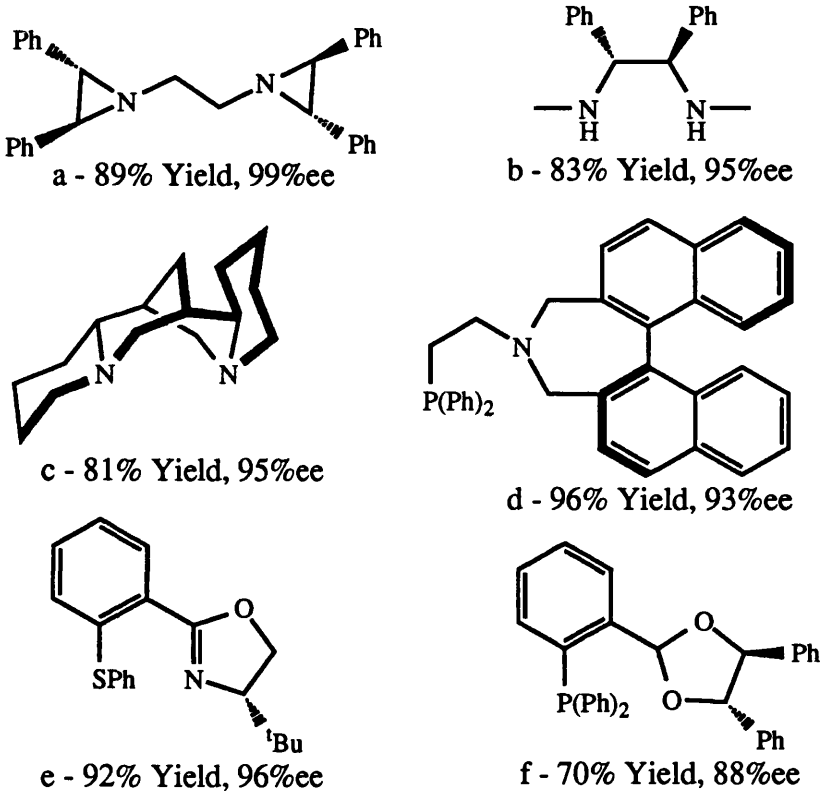
Several recent publications[20] have shown that it is possible to produce more generally applicable *di*phosphine ligands that also have a significant electronic difference between their coordinating atoms. Simple variation of substituents on one of the P(III) centres can give unusually good selectivity.




Scheme 1.4.b.7

In the reaction (Scheme 1.4.b.7) using ligand **10a** the electronic *and* steric effects are acting in a cooperative manner.

To summarise, a large number of ligands of many different classes have been used in this reaction. Each class of ligand achieves its enantioselectivity in a slightly different manner (see Figure 1.4.b.8).[21] The yields and enantiomeric excesses shown refer to the use of each ligand in the reaction shown in Scheme 1.4.b.1.




a - 89% Yield, 99%ee

b - 83% Yield, 95%ee

c - 81% Yield, 95%ee

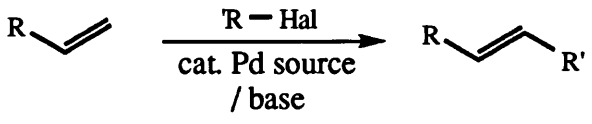
d - 96% Yield, 93%ee

e - 92% Yield, 96%ee

f - 70% Yield, 88%ee

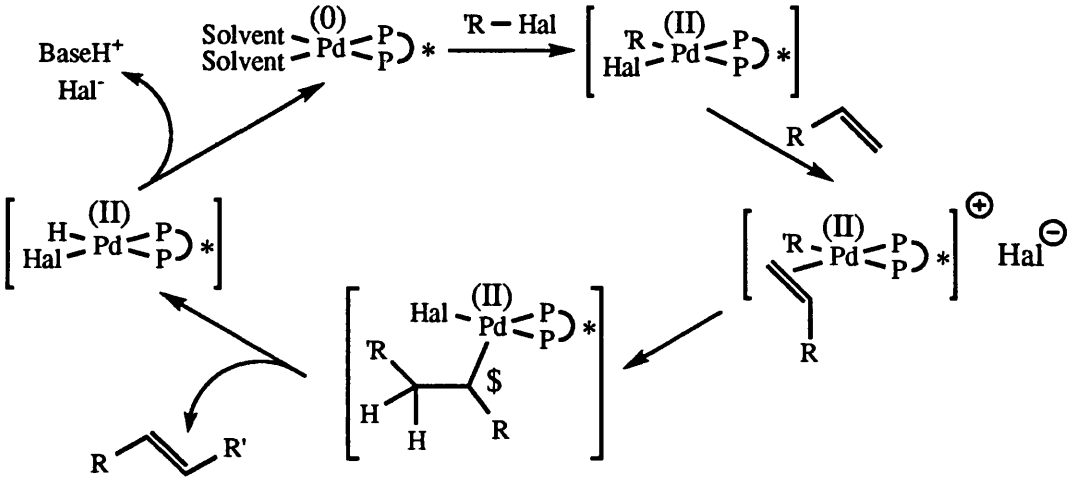
Figure 1.4.b.8

c. Asymmetric Heck reaction: The classical Heck reaction involves the formation of an $sp^2$ C-C bond (see Scheme 1.4.c.1) and can thus only have geometrical rather than stereochemical implications.



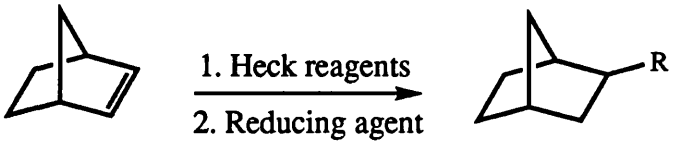

Scheme 1.4.c.1

This reaction proceeds in several discrete stages (see Scheme 1.4.c.2). Initially the halide oxidatively adds to the Pd centre forming an alkyl Pd halide, then the olefin associates with the Pd species. Elimination of the product olefin is then followed by reductive elimination of hydrohalic acid (which is trapped by the base present) thus allowing the Pd to re-enter the catalytic cycle.




Scheme 1.4.c.2

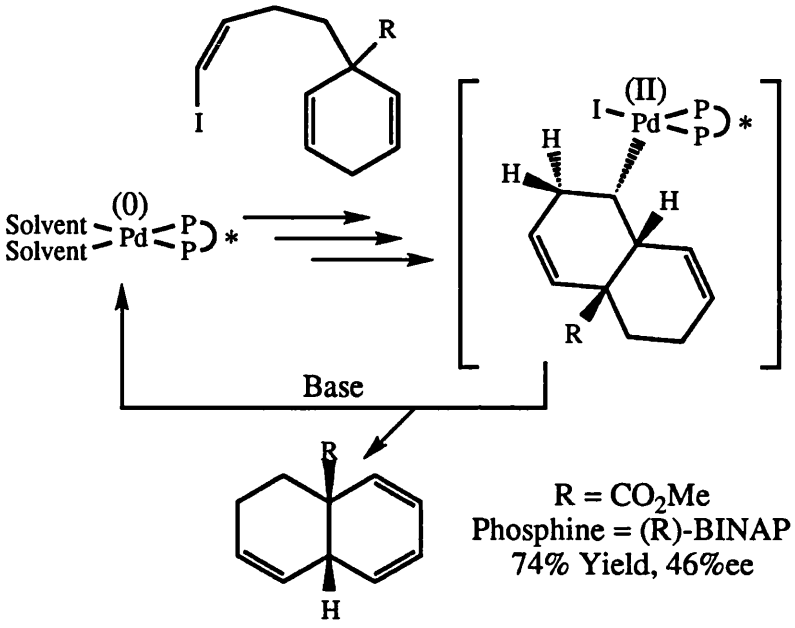
If β-elimination is suppressed an alternative is to trap the final Pd halide intermediate with another nucleophile.




Scheme 1.4.c.3

In the system shown in Scheme 1.4.c.3[23] there are two points to note. The bicyclic skeleton does not allow the formation of a bridge-head double bond, so the alkyl palladium species formed does not β-eliminate. The skeleton also determines that only the *exo*-isomer is formed. The overall transformation observed is essentially a hydro-alkylation of an unactivated C=C.

If β-elimination is highly favoured, or possible *only* away from the initially formed $sp^3$ centre (marked $, Scheme 1.4.c.2) then a stereogenic centre is formed. In the example shown in Scheme 1.4.c.4[22] it is only possible to β-eliminate from the methylene because the methyne proton and the Pd complex cannot obtain the necessary relative *syn*-orientation.

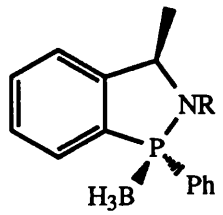



Scheme 1.4.c.4

1.5 Ligand design rationale:

Section 1.4 described three particular catalytic asymmetric reactions. There are many more. Each type of reaction and substrate has subtly different ligand requirements and thus there is room for an extremely large number of ligands. This project was conceived to research the directing abilities of a new family of phosphine ligands derived from compounds containing the dihydrobenzazaphosphole-borane moiety, **11** (see Figure 1.5). The ligands themselves will be obtained from compounds such as **11** by *in-situ* deboration, coordination to a metal centre then occurring via the deprotected P(III) centre.

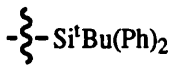
Figure 1.5

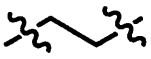



(R)-*trans*-**11**

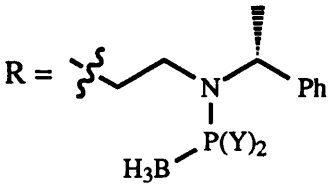
R = 


Where $X(Y)_n$ is an achiral coordinating group

R = 


R = 

A dimeric ligand

R = 


Y = alkyl, cycloalkyl, aryl

Compound **11** has several noteworthy points;

a. Position of chirality; In the literature[24] few phosphine ligands are chiral at phosphorus, thus removing the primary chiral environment at least two bonds from the metal centre when the ligand is bound in the active complex. This is primarily because of the general difficulty in synthesising phosphorus compounds chiral at phosphorus. Exploration of new methodology in this area should give useful insights into P(III) chemistry.

b. Rigid conformation; The rigidity of the pentacycle containing the phosphorus atom gives the ligand a high degree of conformational stability. This ensures that the two phenyl rings attached to P are held at a constant relative position, increasing the likelihood of a 'half-propeller' arrangement being formed. This arrangement of phenyl rings is found in the highly successful BINAP, **8**, see Figure 1.3.c.

c. Borane protection; Although borane protection of P(III) centres against oxidation has been used both in synthesis[25] and in phosphine ligand protection[39] the full scope of its applicability has not been described. Air-stable, easily handled ligands are practically much preferable to those that are unstable to oxygen. A one-pot deboration, complex formation reaction was envisaged, such that no handling of unprotected P(III) compounds was necessary.

Hence, this project is the study of the rational design, synthesis and screening of several members of the compound family containing the dihydrobenzazaphosphole-borane moiety.

# 2. The Initial Target

## 2.1 General considerations:

At the beginning of my thesis current literature on palladium catalysed allylation chemistry[27] suggested that this presented a good opportunity to test out the directing ability of the dihydrobenzazaphosphole core. Mechanistic considerations (see section 1.4.b) coupled with synthetic possibilities suggested that a chelating, bidentate ligand, **12** (Figure 2.1), be designed such that $X(Y)_n$ was an achiral coordinating group.

**12**

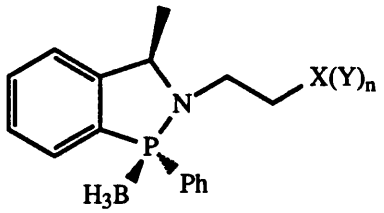


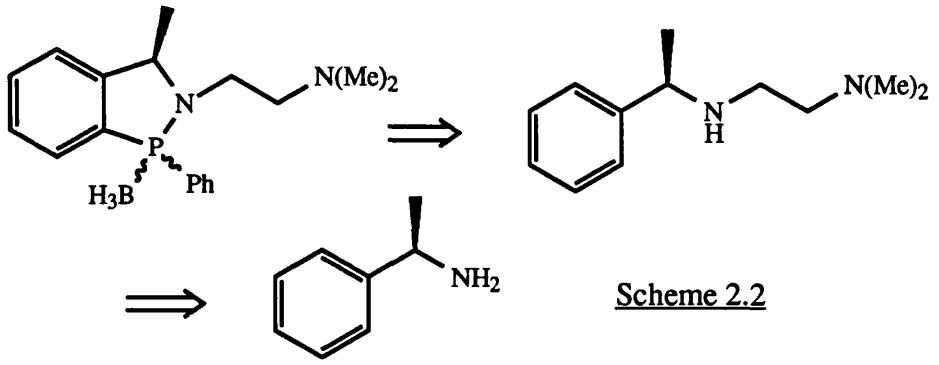

Figure 2.1

As discussed in section 1.4.b, atom X could theoretically be virtually any element with an available lone-pair of electrons. However, synthetically the range of reasonable choices is somewhat smaller. Pd(0) is not very oxophilic so general literature on chelating bidentate ligands suggested that nitrogen, phosphorus and sulphur were practical and synthetically possible alternatives.

Simple retrosynthetic analysis (see section 2.2) suggested that deprotonation α to phosphorus could prove problematic so a ligand with electronically different donor atoms was examined. Current literature[27] suggested that nitrogen gave good results with Pd(0) species in this reaction, thus, in the initial target X became nitrogen.

For maximum simplification a tertiary amine was considered, potentially problematic acidic protons thus being avoided.

2.2 Retrosynthesis:




Scheme 2.2

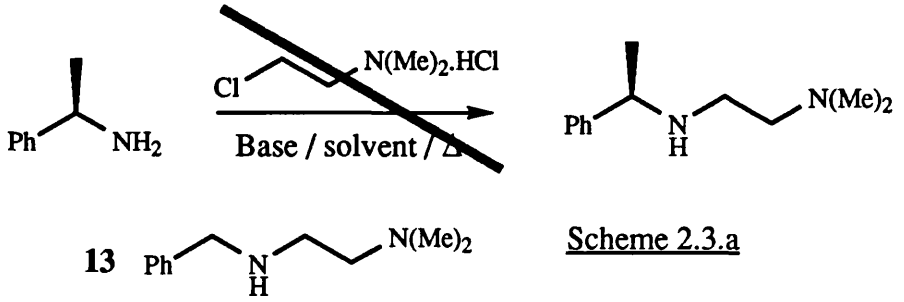
(R)-(α)-methyl benzylamine

Alkylation of (α)-methyl benzylamine, available commercially in either pure antipode, followed by *ortho*-lithiation, quenching with a phosphorus electrophile and addition of a borane source were the anticipated synthetic steps. This would give a mixture of diastereomers, the (α)-methyl allowing their separation and thus giving two ligands that were enantiomeric at phosphorus.

2.3 Synthetic approaches:

Three basic strategies were examined.

a. Simple alkylation: By analogy with a reference[28] to the preparation of **13**, alkylation of (α)-methyl benzylamine with dimethylaminoethyl chloride hydrochloride was attempted. This proved very capricious and under the few conditions that did give product, removal of starting materials proved impossible.



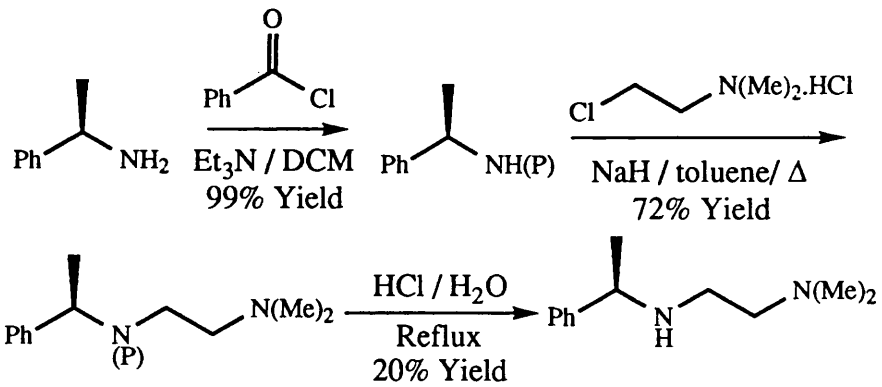

**13** 


Scheme 2.3.a

b. Alkylation after N-protection; With N-monoprotected (α)-methyl benzylamine deprotonation was possible, enhancing reactivity and thus allowing complete consumption of starting materials which, in turn, alleviated problems of purification.

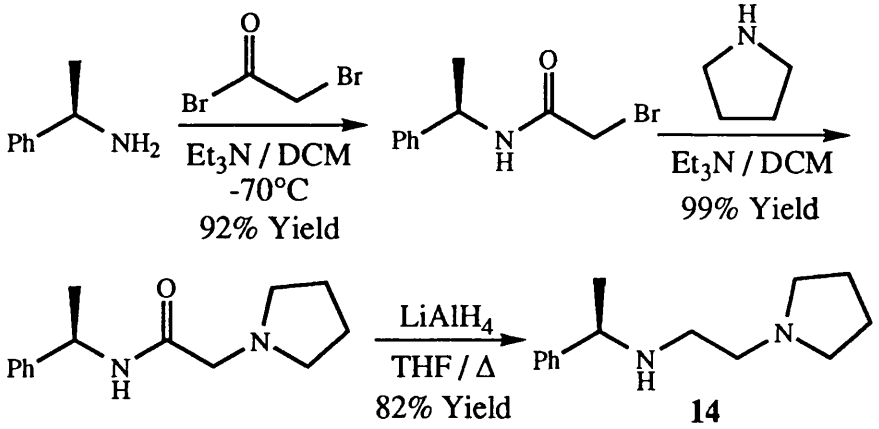
Limited experiment with benzoyl (see Scheme 2.3.b) and *tert*-butyloxycarbonyl ($^t$BOC) protecting groups gave variable yields *all of which were much lower than comparable experiments using benzylamine.* This was the first of many instances in which the (α)-methyl proved to have an unexpectedly large effect on the outcome of a reaction.

Problems with reproducibility and the lack of flexibility in this scheme prompted further investigation.




Scheme 2.3.b

c. Stepwise addition; In the search for greater flexibility an electrophilic material was sought which would give an addition product with (α)-methyl benzylamine which was itself also electrophilic (see Scheme 2.3.c). Bromoacetyl bromide proved ideal. Sequential reaction with (α)-methyl benzylamine and then pyrrolidine, under suitable conditions, followed by reduction gave high yields of **14**.




Scheme 2.3.c

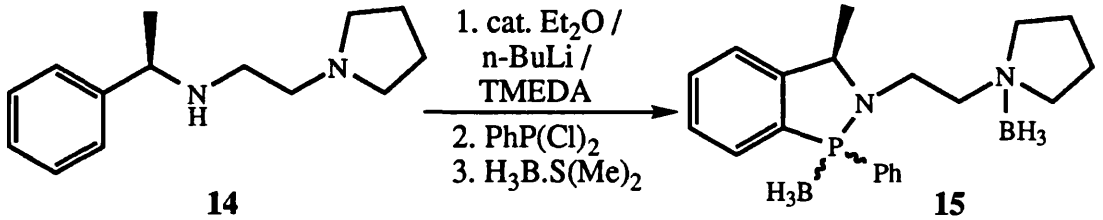
Although the original target was the N,N-dimethyl relative of **14** the pyrrolidyl substituent proved easier to purify to the analytical standard needed for the *ortho*-lithiation to follow.

This proved a far superior route to those shown in scheme 2.3.a and scheme 2.3.b and allowed large amounts (>25g) of **14** to be prepared very quickly. Both the bromo-amide and the amino-amide are crystalline solids so purification and material recovery was very easy.

# 3. Cyclisation

3.1 *Ortho*-lithiation:

In the retrosynthetic analysis shown in section 2.2 the final synthetic step is an *ortho*-lithiation of diamine **14** followed by quenching of the resulting bis-anion with dichlorophenyl phosphine. The P(III) centre was to be protected against oxidation by forming the borane adduct.




**14** **15**

Scheme 3.1

A brief foray into the literature indicated the wide variety of conditions used for *ortho*-lithiation. A short series of experiments provided the reason - extreme substrate specificity.

a. Substrate concentration: Virtually all true *ortho*-lithiations, in contrast to halogen exchange reactions, seem to require a reasonably high substrate concentration. Initially an approximately 1M solution of base was employed (equal volumes of ether and n-BuLi) but it was not until the ether was *omitted*, except for a catalytic amount[29], that *ortho*-lithiation was observed.

b. Butyllithium concentration: Examination of the experimental sections of several references revealed that virtually all experiments are carried out using 2.5M butyllithium. It was found that *negligible ortho*-lithiation is observed if the concentration of the butyllithium used falls below 2.0M. This may seem to be a very simple corollary of the section above, but if 8.7M butyllithium is used very low yields of product are observed. This may well be due to the larger amount of LiOH present hydrolysing the product.

c. TMEDA; Literature again indicates TMEDA activates n-butyllithium to give a higher yield of *ortho*-lithiation. Reactions with and without TMEDA proved this point, no reaction occurring until at least 0.5 equivalents of TMEDA was present.

d. Solvent; Strong lithium bases are generally used in solvents such as THF, ether, toluene and hexane, so initially the reaction was attempted in ether and THF, solubility of the mono-anion being the main concern. At that time a reference[30] appeared that gave the temperature dependence and half-lives of various lithium bases in various solvents. Since an overnight reaction at room temperature seemed to be necessary, this ruled out the use of THF (the half-life of n-BuLi / TMEDA / THF / 20°C = 38 ± 3 mins). As has previously been stated, ultimately only a catalytic amount of ether was used, the mono-anion fortunately being soluble in hexane above about 10°C at the concentration used.

A short series of experiments forming the *ortho*-anion of **14** under various conditions, and trapping it with benzaldehyde at -70°C, gave a good insight into the necessary conditions for successful reaction (Table 3.1).

Table 3.1 - *Ortho*-lithiation and trapping of **14** with benzaldehyde

| Conditions | Yield (%) | Conclusions |
|---|---|---|
| n-BuLi / ether / r.t. / overnight | 0 | |
| n-BuLi / ether / TMEDA / r.t. / overnight | 30-40 | TMEDA essential |
| n-BuLi / cat. ether / TMEDA / r.t. / overnight | ca. 90 | High concentration needed |
| t-BuLi / ether / -15°C / 3hrs | 0 | |
| t-BuLi / cat. ether / -15°C / 3hrs | 0 | |
| t-BuLi / cat. ether / TMEDA / -15°C / 3hrs | <10 | |

Yield refers to amount of product formed on addition of benzaldehyde at -70°C.
"ether" - an equal volume of ether to BuLi used.
"cat. ether" - < 0.5ml / g substrate used
n-BuLi titrating to 2.2 - 2.4M and t-BuLi titrating to 1.7M was used. If 1.6M n-BuLi was used no *ortho*-lithiation was observed.

3.2 Quenching and boration:

Quenching the bis-anion generated by *ortho*-lithiation with phenylphosphine dichloride produces two moles of LiCl as a solid precipitate. Unfortunately, because of the high concentration used, more solvent must be added prior to quenching the reaction to allow reasonable agitation of the solution. This apparently simple operation is critical to the boration step later on.

- If hexane is used, flocculation of the suspended solids occurs when borane-dimethyl sulphide complex is added, preventing stirring and completion of reaction.[31]
- If THF is used, the yield of product suffers significantly, presumably because of the destruction of solvent by deprotonation by anionic species present.[30]
- If ether is used, at least four times the volume of n-butyllithium used must be added to prevent flocculation.

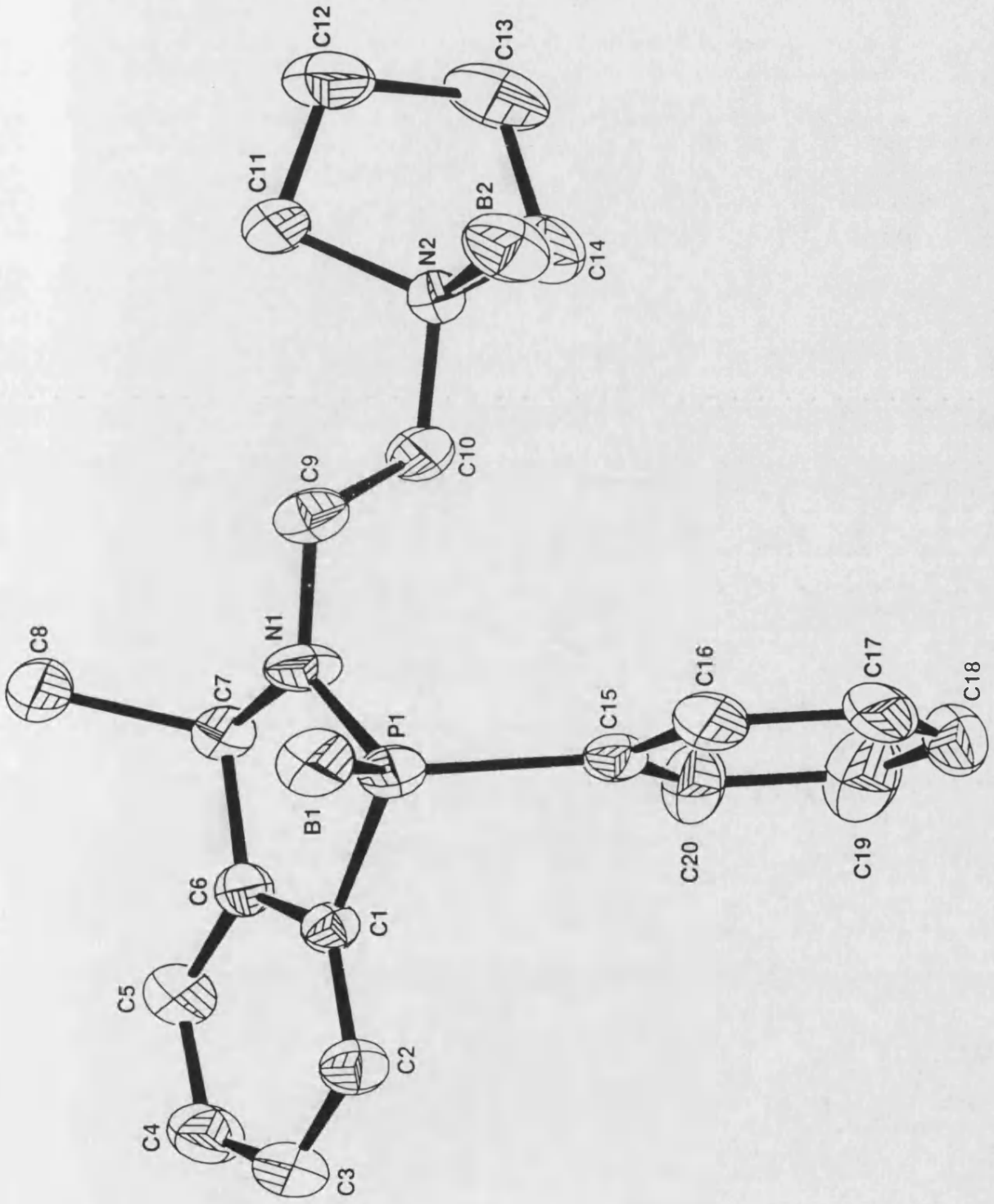
In all, a surprisingly complex answer to an apparently minor problem.

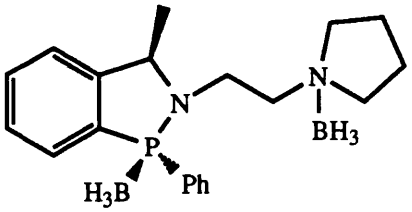
Borane protection of P(III) centres is quick and convenient. In this instance another equivalent of borane source was added to complex the pyrollidyl nitrogen. This made the product compound much less polar and more easily handled.

3.3 Purification:

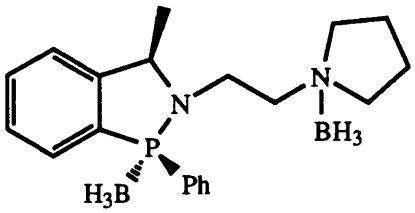
Preliminary experiments showed that careful column chromatography was sufficient to provide samples of each of the diastereomers of **15**. Extensive thin layer chromatography using eleven different solvent systems and numerous visualisation techniques showed that each of these were apparently single compounds. Reverse phase HPLC confirmed this.[32] Much time and effort were spent trying to crystallise the less polar diastereomer - to date all samples have remained oils. However, the more polar diastereomer was crystallised from a DCM / hexane mixture and X-ray crystallographic analysis[33] showed it to have a *trans* relationship between (α)-methyl and phenyl groups (see Figure 3.3.a and 3.3.b).

Figure 3.3.a - X-ray crystallographic structure of (R)-*trans*-**15**






(R)-*trans*-**15**
More polar diastereomer
Crystalline




(R)-*cis*-**15**
Less polar diastereomer
Non-crystalline

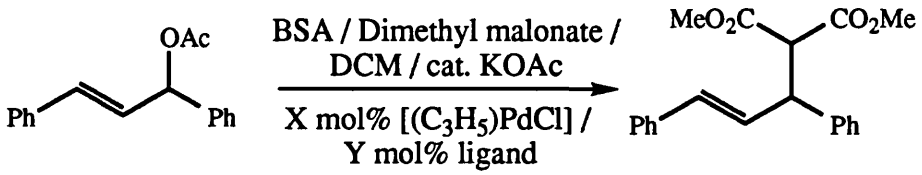
Figure 3.3.b

Two noteworthy points emerged from this analysis. The two phenyl rings are orthogonal to each other thus giving a 'half-propeller' array (see section 1.5.b). There are two molecules of $BH_3$ incorporated into the structure of *trans*-**15**. One molecule is complexed to the pyrollidyl nitrogen and the other is complexed to the phosphorus atom. *No $BH_3$ is complexed to the nitrogen in the dihydrobenzazaphosphole ring*. This suggests that the lone-pair on this atom is not available for coordination to $BH_3$ and that coordination of the deborated analogue of *trans*-**15** to a metal centre will be via the pyrollidyl nitrogen and phosphorus only.

# 4. Primary Screening

4.1 Selection of a model reaction:

As stated in section 2.1, recent literature on Pd(0) catalysed allylic alkylation reactions[27] suggested that this might be an interesting reaction to gauge potential enantioinduction of dihydrobenzazaphosphole type ligands. The relative abundance of information on procedures, and the ease of determining the enantiomeric excess of the product, a simple chiral shift agent NMR experiment,[34] proved very attractive.




Scheme 4.1

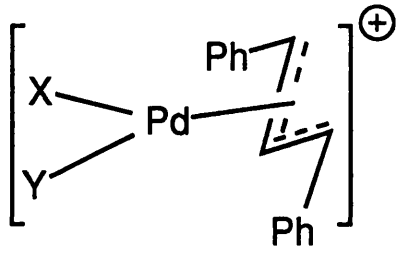
At this point an explanation of how the deborated relative of **15** was expected to give an enantioinduction in this reaction is necessary.

4.2 Theory of ligand selectivity:

Section 1.4.b gives a general introduction to enantioselective Pd allyl substitution reactions involving **16** (Figure 4.2.a).

X, Y = Ligands

Figure 4.2.a




**16**

There are two main problems to address. The first is to bias which end of the symmetrical allyl system any nucleophile will attack. We hoped to use the electronic difference between the two donor atoms in the manner described in section 1.4.b. The second major problem that must be overcome is that the allyl system can complex with the Pd atom in two geometrical conformations. Figure 4.2.b outlines these possibilities using deborated (R)-*cis*-**15** as the ligand. It was hoped that the severe steric interaction between the ligand and allyl system in the 'W' configuration would make this configuration highly disfavoured.

Combining these two controlling influences shows the predicted enantiomer of product favoured by the deborated relative of (R)-*cis*-**15**.

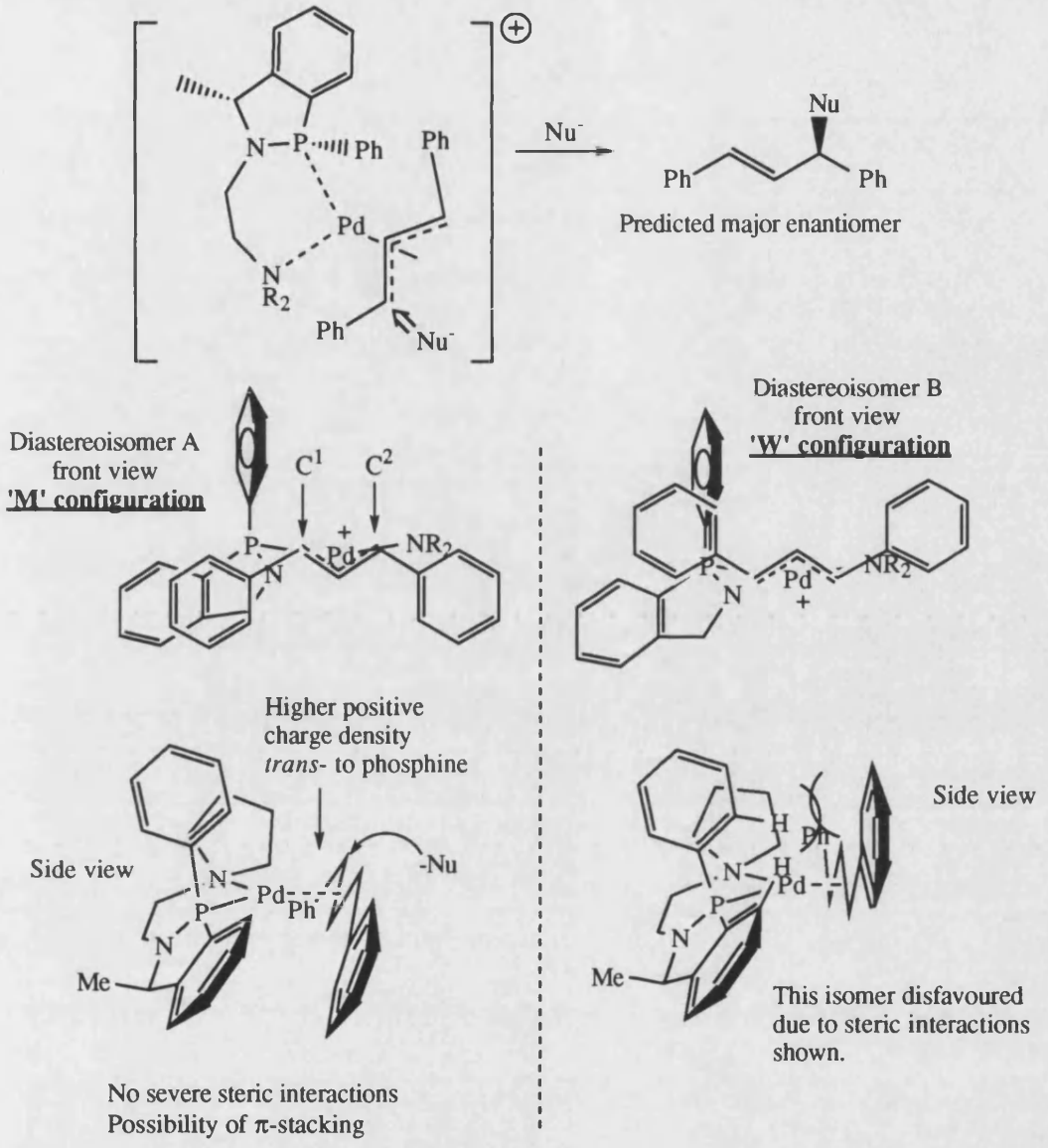



Figure 4.2.b - Control of nucleophilic attack on allylic ligands attached to Pd complexes

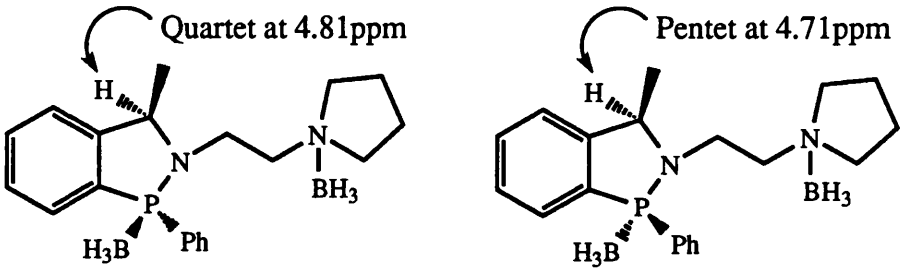
4.3 Preparation of an active ligand:

For compound **15** to be converted to a chelating ligand the lone-pairs on phosphorus and nitrogen used in coordinate bonds with borane must be freed.

Several deboration procedures are known[35] using an excess of various secondary amines. These all require prolonged heating and it was felt that an alternative should be developed to try and remove the possibility of thermal epimerisation at phosphorus.

Tributylphosphine has a strong affinity for borane and efficiently deprotects both phosphorus and nitrogen at room temperature.[36] Unfortunately tributylphosphine also forms an extraordinarily active catalyst with palladium[37] and even at micromolar concentrations this achiral catalyst is more efficient in the allylic alkylation reaction than chiral *trans*-**15**, thus leading to racemic product.

The $^1$H NMR of **15** shows one very characteristic signal that can be used to determine the diastereomeric purity of the sample. The proton at the base of the (α)-methyl (see Figure 4.3.a) shows a quartet at 4.81ppm in *trans*-**15** whereas *cis*-**15** gives a pentet at 4.71ppm. These signals do not overlap and give base-line resolution.

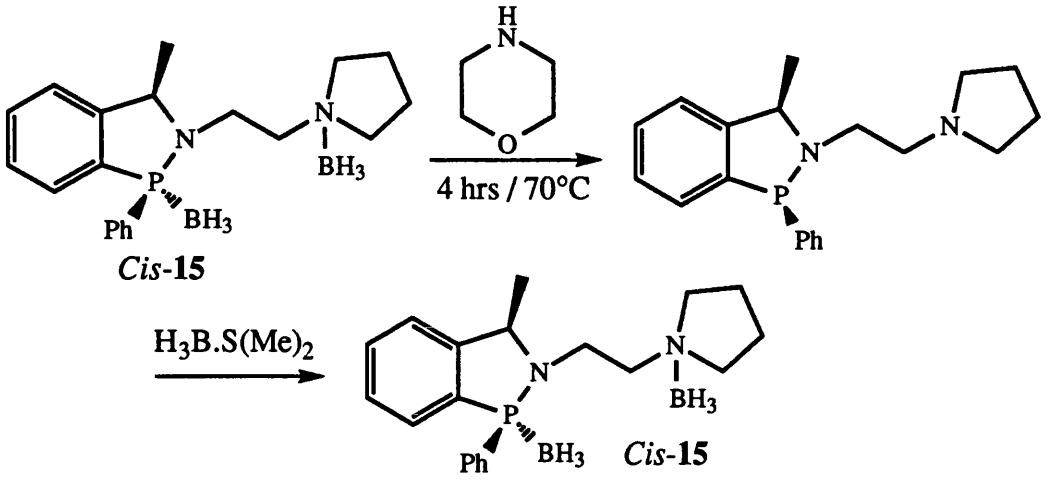



(R)-*trans*-**15**
More polar diastereomer
Crystalline

(R)-*cis*-**15**
Less polar diastereomer
Non-crystalline

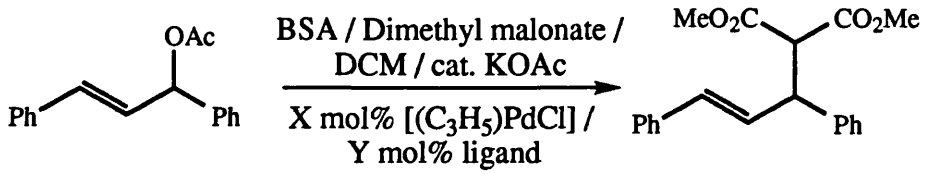
Figure 4.3.a

Following a reference[35], morpholine was used in an attempt to check for thermal epimerisation at phosphorus by NMR (see Scheme 4.3.b). Reaction of *cis*-**15** with morpholine at 70°C for 4 hours was followed by removal of excess morpholine under reduced pressure. Cooling to RT, dissolution in DCM and addition of excess borane-dimethyl sulphide complex gave recovery of starting material. NMR showed very little, if any epimerisation of the phosphorus centre. However, an exactly analogous experiment using *trans*-**15** gave 5-10% epimerisation of the phosphorus centre after only 2 hours at 70°C.




Scheme 4.3.b

4.4 Initial screening:




Scheme 4.1

Following deboration of the appropriate amount of ligand precursor, *trans*- or *cis*-**15**, using morpholine as solvent at 70°C for 2 hours, excess morpholine was removed under vacuum at 0.2mmHg and 70°C for 10 minutes. Allowing this to cool to room temperature resulted in formation of an opaque white gum, containing deborated **15** and borane-morpholine complex, to which was added a solution of $[(C_3H_5)PdCl]_2$ in dry, degassed DCM. This yellow solution was refluxed for 2 hours, during which time it darkened to give a deep red solution containing the active ligand complex. Sequential addition of a solution of the substrate in dry, degassed DCM, BSA, dimethyl malonate and a catalytic amount of KOAc initiated the reaction.

In the first attempts at this reaction freeze-thaw degassing cycles were used[38] but on closer inspection of the results obtained these seemed to deactivate the ligand

complex and four or five vacuum-argon cycles using a vacuum line were substituted to ensure deoxygenation of the solution.

Table 4.1

| Ligand | Mol% Pd | Mol% Ligand | Deboration Method | Yield | %ee[34] | Configuration |
|---|---|---|---|---|---|---|
| *Trans-15* | 4 | 10 | Morpholine | 86 | 60 | R |
| *Cis-15* | 4 | 10 | Morpholine | 35 | 33 | S |

The above results (Table 4.1) show that the model proposed in section 4.2 predicts the correct configuration of the major product. The yield and %ee for *cis*-**15** were low and variable and reflect the fact that *trans*-**15** is crystalline and can thus be purified to a much higher standard than non-crystalline *cis*-**15**.

At about the time that this work was being carried out a reference to a new method of deboration appeared.[39] This involved stirring a toluene solution of **15** with two equivalents of DABCO at 40°C for 2 hours and then removing the toluene under reduced pressure. The deprotected **15** and borane-DABCO mixture was then used as previously described (Table 4.2).

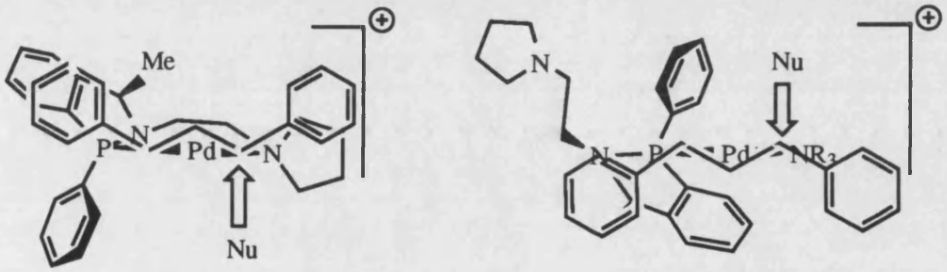
Table 4.2

| Ligand | Mol% Pd | Mol% Ligand | Deboration Method | Yield | %ee | Configuration |
|---|---|---|---|---|---|---|
| *Cis*-**15** | 4 | 10 | DABCO | 51 | 6 | S |
| ***Trans-15*** | **4** | **10** | **DABCO** | **99** | **62** | **S** |

Possibly for reasons of purity as discussed above, when used in the reaction shown in Scheme 4.1, *cis*-**15** unfortunately gave a very low %ee with a slightly improved yield.

However *trans*-**15** gave the enantiomer *opposite* to that expected in very similar %ee to the morpholine deboration procedure. After careful consideration one possibility was that the pyrollidyl moiety of the ligand was being displaced from the Pd(0) complex by a molecule of DABCO or DABCO-borane complex. The nucleophilic attack still occurs *trans* to the P(III) centre, but if the ligand is only acting as a monodentate entity the bulky pyrollidyl moiety will be forced out away from the Pd complex on steric grounds (see Figure 4.4). This leads to the opposite enantiomer being formed preferentially.

To test this hypothesis a monodentate ligand containing the dihydrobenzazaphosphole core and having a very large, non-coordinating substituent on nitrogen was needed.




Morpholine deboration
gives R-(+) enantiomer

$NR_3$ = DABCO

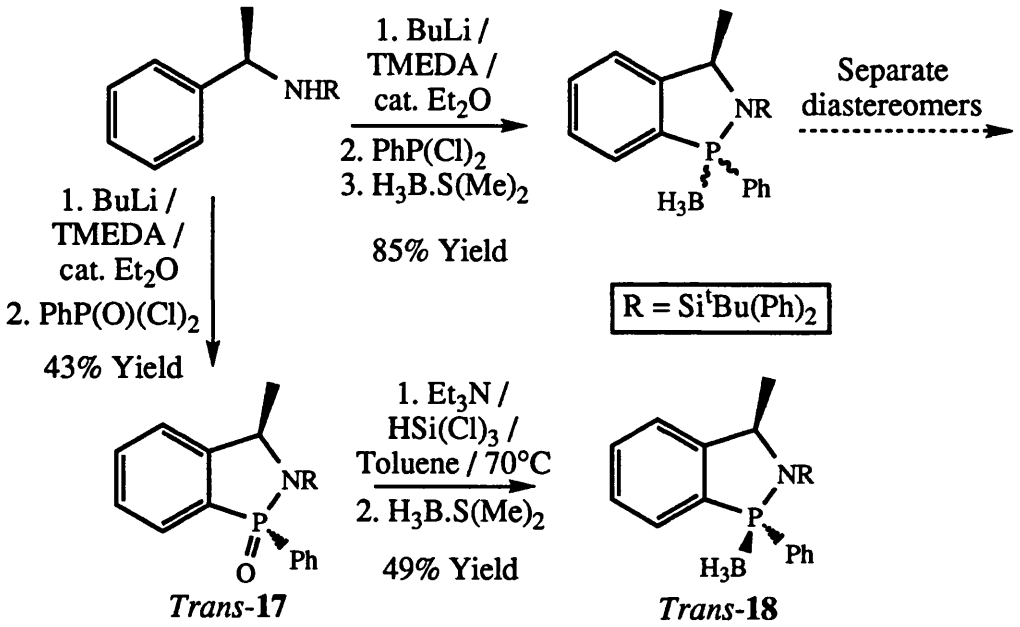
DABCO deboration
gives S-(-) enantiomer

Figure 4.4

# 5. Monodentate Ligand

5.1 Synthesis:

The basic tenet that a very large non-coordinating group was needed on the nitrogen of the dihydrobenzazaphosphole moiety suggested that a bulky silyl protecting group at this position would be valuable. Silylation of (α)-methyl benzylamine[40] followed by *ortho*-lithiation, quenching with a P(III) electrophile and borane protection was predicted to furnish a mixture of diastereomers of a candidate compound.




Scheme 5.1.a

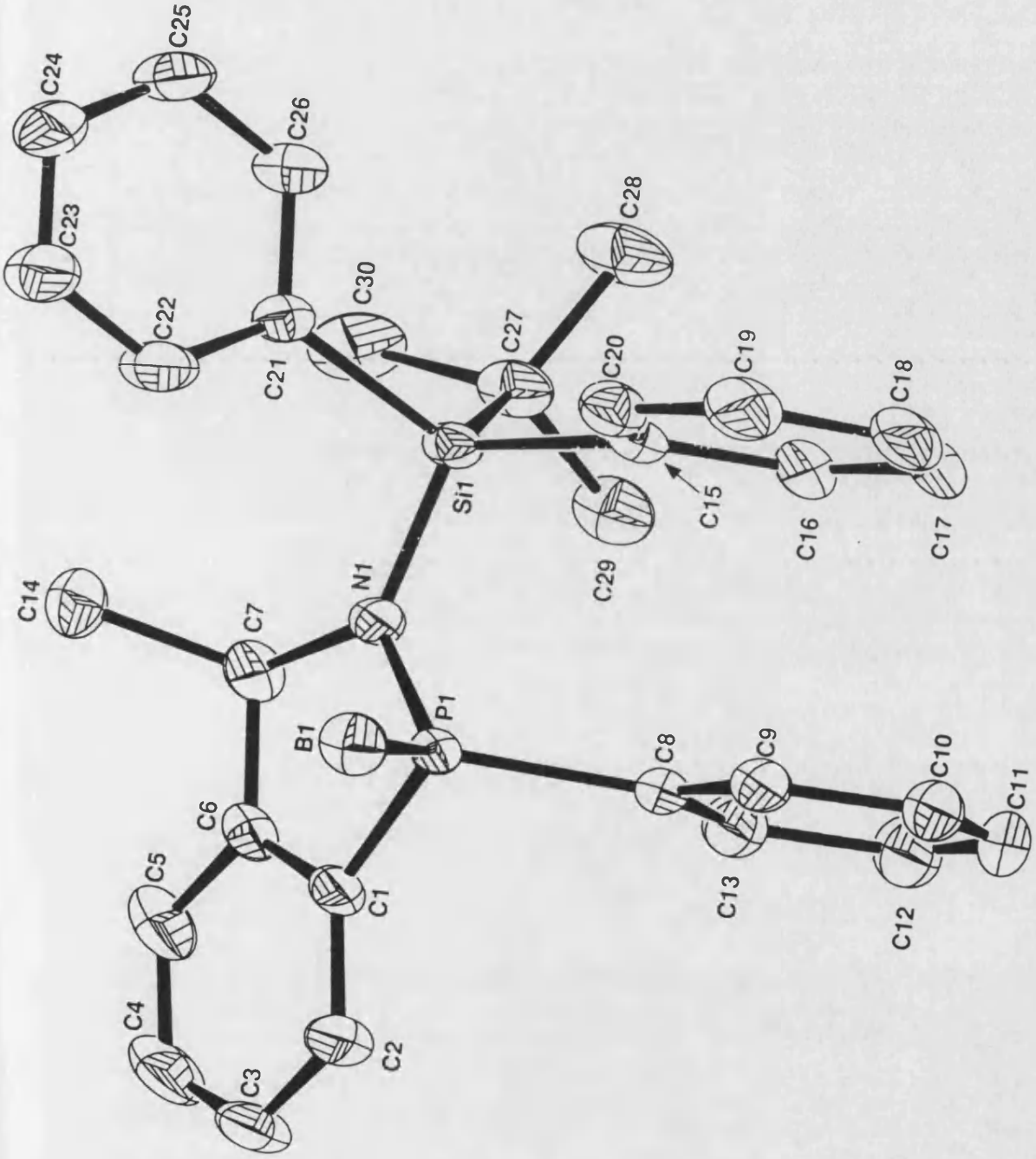
Using the *tert*-butyldiphenyl silyl protecting group *ortho*-lithiation[41] was achieved in high yield using vigorous conditions (Scheme 5.1.a). Quenching and boration also gave good yields of a 1:1 mixture of diastereomers of **18**. Unfortunately, these proved to be inseparable by column chromatography so a diastereoselective route was required.

A previous worker[42] had made compound **17** in diastereomerically pure form, as confirmed by X-ray crystallography. Simple reduction and boration of this substrate

produced a single diastereomer of **18**. X-ray crystallographic analysis (see Figure 5.1.b) proved that this was *trans*-**18**.[33] Again (see section 3.3) there are two noteworthy points to be gleaned from this analysis. The two phenyl rings attached to the phosphorus atom are orthogonal leading to a 'half-propeller' array (see section 1.5.b).

Boration has again occurred on the phosphorus atom and this suggests that it will be through the phosphorus atom that the deborated relative of *trans*-**18** binds to any metal centre.

Figure 5.1.b - X-ray crystallographic structure of (R)-*trans*-**18**

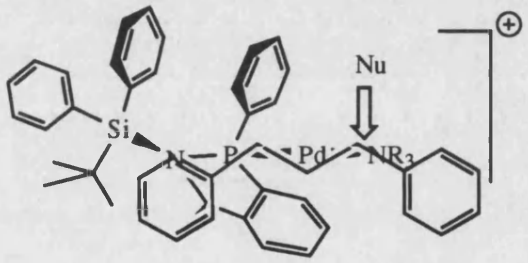


5.2 Screening the monodentate ligand:

Using *trans*-**18** under exactly the same conditions as for **15** in the allylic alkylation reaction, shown in Scheme 4.1, gave spectacular results (Table 5.1).

Table 5.1

| Ligand | Mol% Pd | Mol% Ligand | Deboration Method | Yield | %ee | Configuration |
|---|---|---|---|---|---|---|
| *Trans*-**18** | 4 | 20 | Morpholine | 56 | 91.5 | S |
| *Trans*-**18** | 4 | 20 | DABCO | 31 | 89 | S |
| *Trans*-**18** | 1 | 5 | Morpholine | 84 | 84 | S |
| *Trans*-**18** | 1 | 5 | DABCO | quant. | 90 | S |




$NR_3$ = DABCO
Gives S-(-) enantiomer
Figure 5.2.a

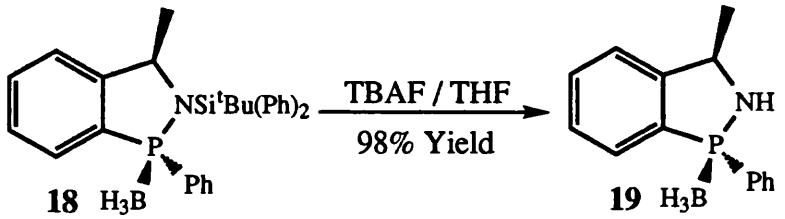
As predicted by the model shown in Figure 5.2.a, the (S)-enantiomer is the major product. The conformation of the ligand is closely related to that of *trans*-**15** when deborated with DABCO (Figure 4.4). However, in this case, the large silyl group suppresses formation of the 'W' conformation complex much more completely and reaction proceeds almost exclusively via the 'M' conformation as shown (Figure 5.2.a). Changing the deboration procedure does not change the major enantiomer produced. However, at the higher ligand and Pd(0) loading shown the yields are very

low. This is caused by the residual borane-amine complex acting as a reducing agent towards the Pd allyl complex giving 1,3-diphenylpropene, **20**.


**20** Figure 5.2.b

Reducing the mole percentage of Pd(0) used from 4 to 1, with concomitant reduction in the amount of ligand used brought yields up to excellent levels without too large an erosion of enantioselectivity.

As further supporting evidence for the proposed allyl complex, *trans*-**18** was desilylated with TBAF in THF (see Scheme 5.2.c) and the resulting compound, *trans*-**19**, used in the allylic alkylation reaction (see Scheme 4.1).




**18** **19**

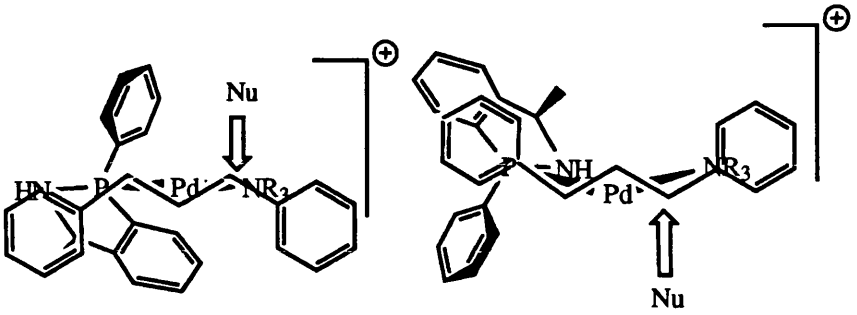
Scheme 5.2.c

Table 5.2

| Ligand | Mol% Pd | Mol% Ligand | Deboration Method | Yield | %ee | Configuration |
|---|---|---|---|---|---|---|
| *Trans*-**19** | 1 | 5 | Morpholine | 95 | 0 | - |
| *Trans*-**19** | 1 | 5 | DABCO | 99 | 0 | - |

Clearly, the large silyl group is playing a pivotal role in the enantioinduction observed (Table 5.2). This can possibly be explained by the model shown in Figure 5.2.d.

Without the large silyl group the ligand is free to rotate around the P-Pd bond and thus give very little enantioselectivity.




$NR_3$ = DABCO

Gives (S)-(-) enantiomer Gives (R)-(+) enantiomer

Deborated (R)-*trans*-**19** used in both diagrams

Figure 5.2.d

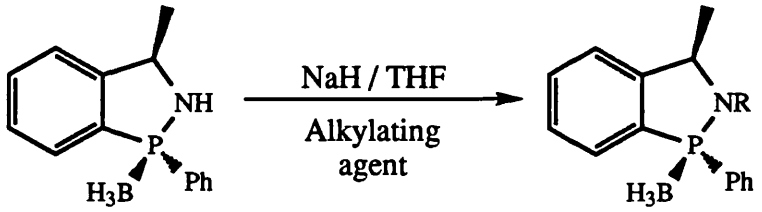
# 6. Further Monodentate Ligands

6.1 Optimisation of ligands:

Although *trans*-**18** gave very high inductions in the allylic alkylation reactions at very low mole percentages, the reaction was slow. By altering the electronic environment of the P(III) centre, fine tuning of the reactivity of the resultant Pd(0) complex should be possible.

There are two obvious places where electronically significant changes can be made relatively easily.

a. N-alkylation: By changing the group attached to the nitrogen atom in the heterocycle it is possible to change the electronics of the P-N bond and the overall steric bulk of the ligand (Scheme 6.1.a).

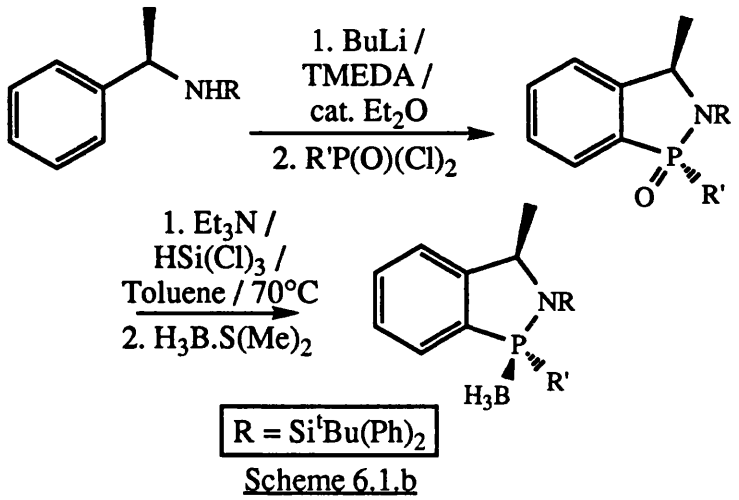



*trans*-**19**

R = $C(Ph)_3$, $Si(^iPr)_3$, $Si(Ph)_3$, etc.

Scheme 6.1.a

b. Changing the phosphine: By changing the substituent on the P(III) centre from a simple phenyl group to 4-methoxyphenyl or pentafluorophenyl it should be possible to alter its π-acceptor nature (Scheme 6.1.b).




R = $Si^tBu(Ph)_2$

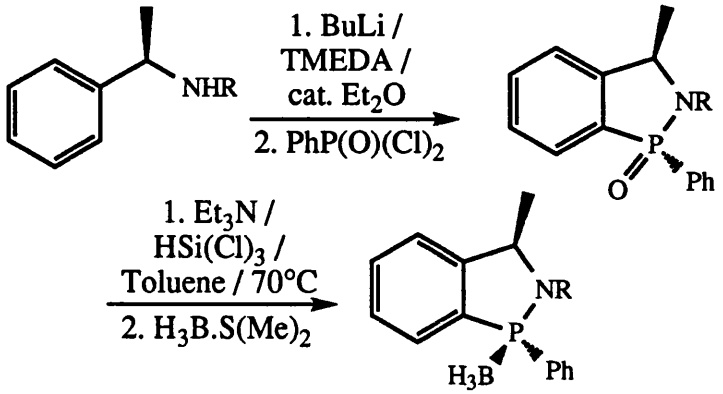
Scheme 6.1.b

This second approach obviously needs much more work and assumes that quenching of the *ortho*-anion would still proceed diastereoselectively, as would reduction of the P(V) compound, which may not necessarily be the case.

Conversely, although low yielding, a route to *trans*-**19** was known.

6.2 Alkylation:

The nitrogen anion of *trans*-**19** has been shown to be extremely basic and virtually non-nucleophilic. It could be methylated, ethylated, benzylated and allylated but any less activated alkylating agent did not react.[43] This led to the conclusion that the only way to introduce different substitution on the nitrogen of *trans*-**19** was to introduce it at the beginning of the synthesis (Scheme 6.2).




R = $C(Ph)_3$, $Si(Ph)_3$, $Si(^iPr)_3$, etc.

Scheme 6.2

This brought us back to the problems of diastereoselectivity in the initial cyclisation and retention of configuration on reduction. Clearly, there was no easy solution to this problem.

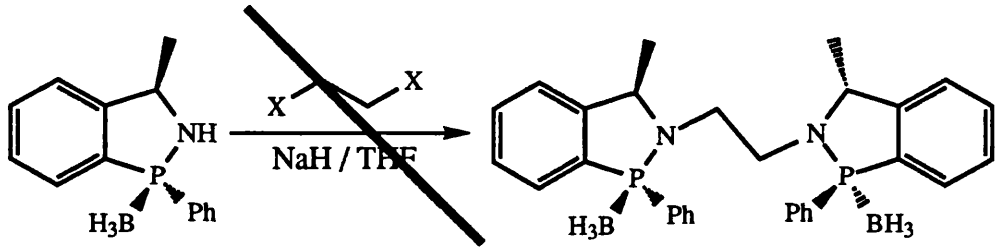
At this time the groups of Williams[12a], Helmchen[12b] and Pfaltz[12c] began to publish extensively in this area. This made further research into ligands specifically for the allylic alkylation reaction much less interesting. A more generally applicable ligand type was needed and this drove the project into the area of diphosphines.

# 7. Dimeric Ligand

## 7.1 Synthetic strategies:

Having established that the dihydrobenzazaphosphole moiety was viable as a ligand for asymmetric catalysis, exploration of further, more generally applicable, derivatives seemed appropriate. The exceptional value of diphosphines in asymmetric synthesis suggested that the next derivative explored should be a dimeric version of the dihydrobenzazaphosphole core.

Previous studies in the group[43] had shown that the approach shown in Scheme 7.1 was not suitable for the synthesis of the target dimer.

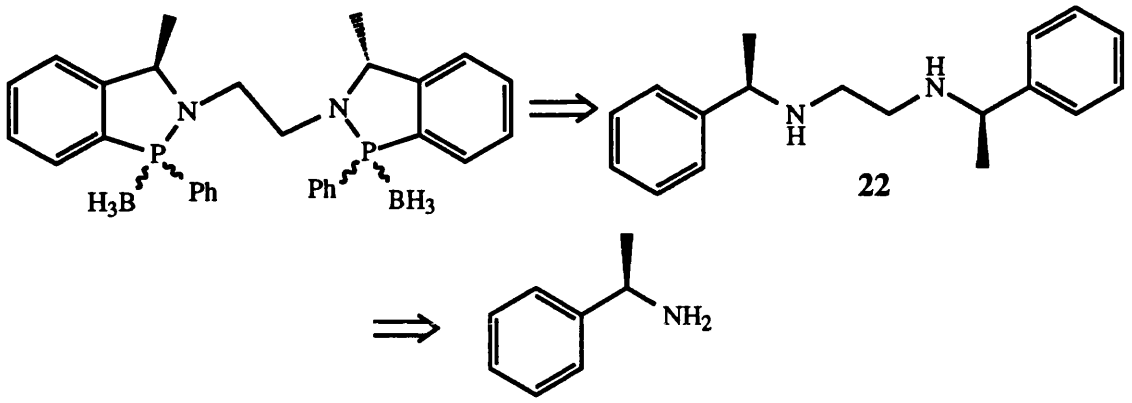



*trans*-**19** *trans,trans*-(R,R)-**21**

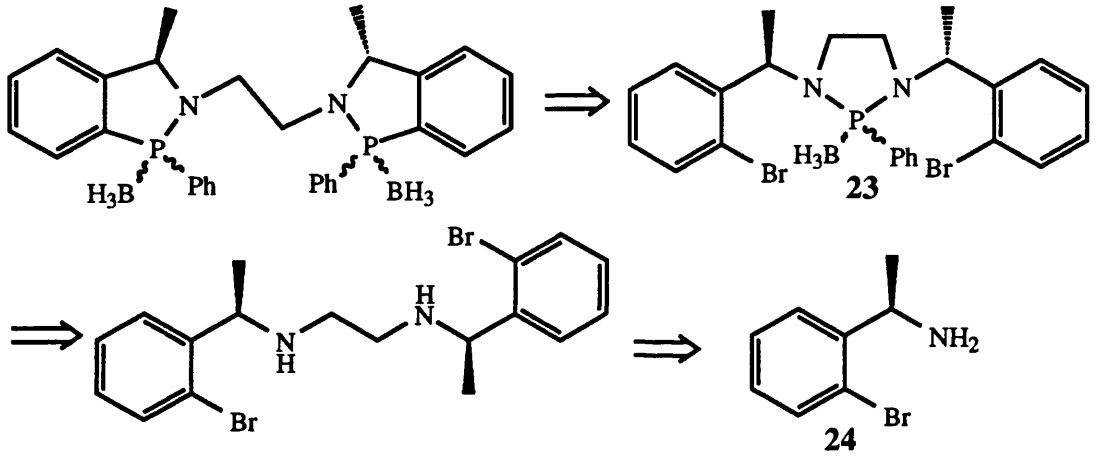
Scheme 7.1

## 7.2 Retrosynthesis:

An alternative strategy was to begin with the ethylene bridge in place and then build both heterocyclic components as outlined in Scheme 7.2.a. The diamine, **22**, is a known compound[44] but converting that, even without considering diastereomers, into **21** involves a double *ortho*-lithiation and formation of a *tetra*-anion. This is *not* overly encouraging but a small conceptual leap led to an attractive strategy which was altogether more workable (Scheme 7.2.b).

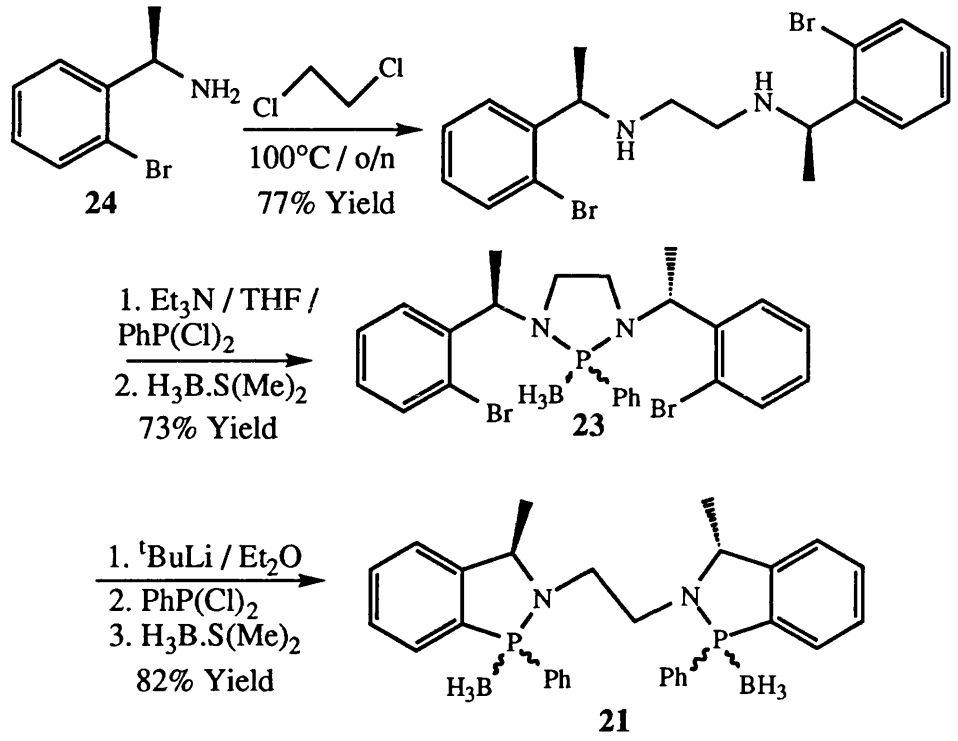



Scheme 7.2.a




Scheme 7.2.b

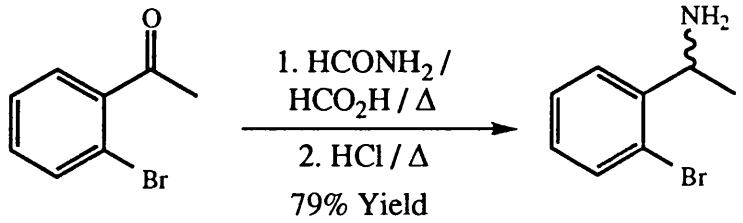
In this case the key intermediate is **23**. The preparation and mechanism by which this is converted into **21** is shown in later sections. Compound **24** is known[45], the dimerisation of the amine has precedent[44], putting a phenylphosphino-borane unit between two secondary amines has been achieved previously[43] and the phenylphosphino-borane unit is known to transfer cleanly under halogen-lithium exchange conditions.[43] All that remains is to trap the *ortho*-anion / nitrogen anion pair with a suitable P(III) electrophile and protect with borane (Scheme 7.2.c). This reaction is not expected to be diastereoselective.




Scheme 7.2.c

7.3 Racemic 2-bromo-(α)-methyl benzylamine:

Since the synthesis of enantiomerically pure **24** was not trivial a validation of the whole synthetic scheme was undertaken with racemic **24** available from 2'-bromoacetophenone by a simple Leuckart amination procedure (Scheme 7.3).[45]




Scheme 7.3

Production of the diastereomeric mixture of diamines proved straight-forward. Trapping this with dichlorophenyl phosphine and borane, to give **23**, also gave no problems. However, although the final reaction certainly gave the correct product, in

what appeared to be reasonably high yield, the number of possible compounds made interpretation of spectroscopic data very difficult. Enantiomerically pure **24** was required.

7.4 (R)-2-bromo-(α)-methyl benzylamine:

The literature method[45] called for a resolution of racemic 2-bromo-(α)-methyl benzylamine using **25** (Figure 7.4.a). Unfortunately, this acid is not commercially available so an alternative route was sought.

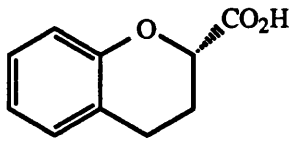
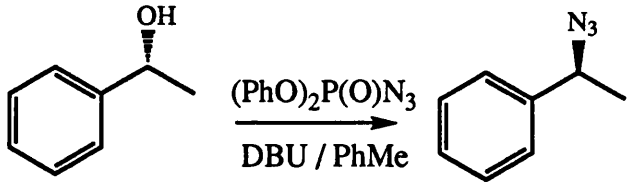



Figure 7.4.a

**25** - (S)-(+)-3,4-dihydro-2H-1-benzopyran-2-carboxylic acid

A brief literature search brought one interesting reference to light.[46] A report by Grabowski gave a procedure for converting enantiomerically pure benzylic alcohols into azides with very little loss of stereochemical integrity (Scheme 7.4.b).

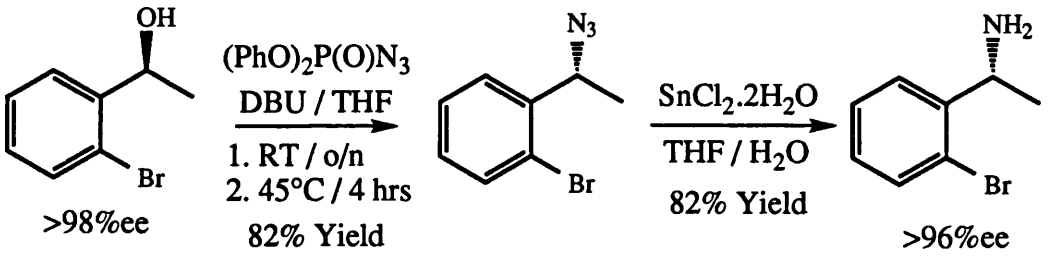



Scheme 7.4.b

Although it is quite expensive, Aldrich do sell (S)-2-bromo-(α)-methyl benzyl alcohol. Generous support from my industrial sponsors, SmithKline Beecham, allowed me to buy 20g.

7.5 The azide displacement:

Grabowski's paper, mentioned above, deals with 3- and 4-substituted aromatic systems varying from highly electron rich to electron poor. With these systems he reports that displacement is complete within several hours at, or below, room temperature. However, the more hindered nature and possible electron withdrawing effect of the 2-bromo substituent in this case led to the need for more vigorous conditions (Scheme 7.5).

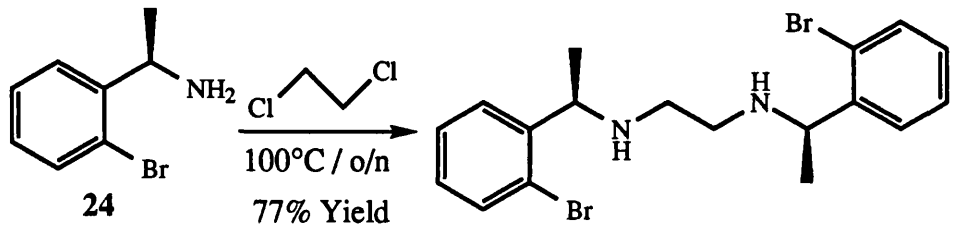



Scheme 7.5

Even with these conditions the stereochemical leakage is very small and it is possible to make large amounts of essentially enantiomerically pure amine.[47]

7.6 Diamine and beyond:

Although practically very simple, addition of 1,2-dichloroethane by syringe-pump to neat amine at 100°C, the synthesis of diamine requires several grams of monoamine precursor. At scales smaller than this it becomes very difficult to prevent the small amount of 1,2-dichloroethane added from condensing onto the cool parts of the reaction vessel, rather than reacting. At smaller scales yields based on 1,2-dichloroethane added also decline sharply, but recovery of unreacted starting amine is still reasonable (Scheme 7.6.a).




Scheme 7.6.a

After an aqueous work-up, extraction, drying and removal of extraction solvent a simple short-path distillation recovers unreacted starting material in very high purity and yield. However, without access to an extremely high-vacuum pump (<0.01mmHg) distillation of the remaining crude product proves very difficult without some thermal decomposition. Using the diamine crude in the next step was not particularly problematic but yields fell by 5-10%.

Previous experiments using racemic **24** gave products with highly complex NMR spectra, as would be expected from a statistical mixture of two possible diastereomeric products, one of which is an enantiomeric pair (see Figure 7.6.b). However, on using (R)-**24** the NMR spectra of the resultant diamine was extremely simple.

Trapping the diamine with phenylphosphine dichloride proved very straight-forward as long as the phosphine was freshly distilled. Even a small percentage of the corresponding phosphinic acid in the phosphine reduced the yield of adduct by 30-40% (Scheme 7.6.c).

Once protected as the borane adduct the heterocycle could be crystallised from a large volume of hexane. Crystallisation removed any traces of the meso- or (S,S)-diastereomer and was essential to ensure that the next step gave a good yield.

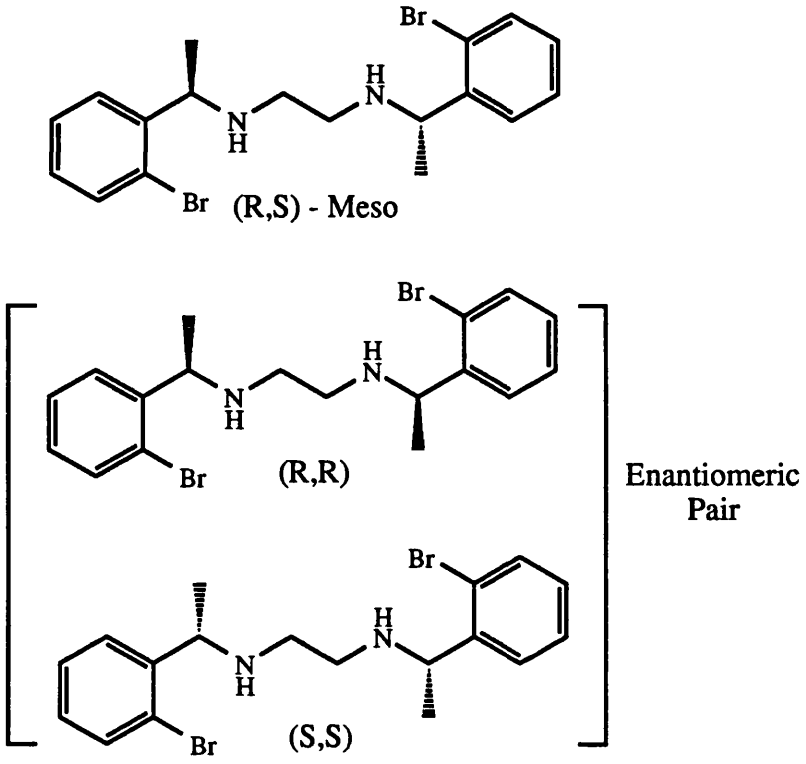
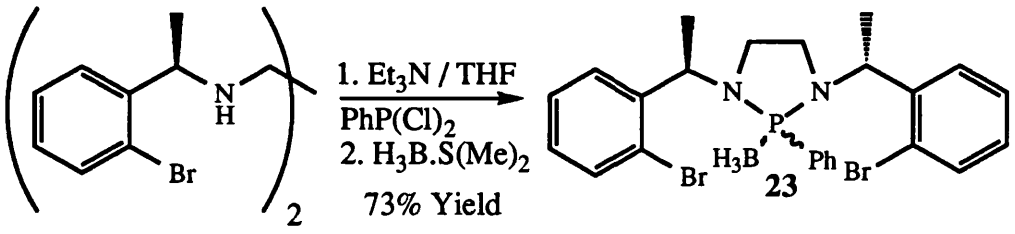
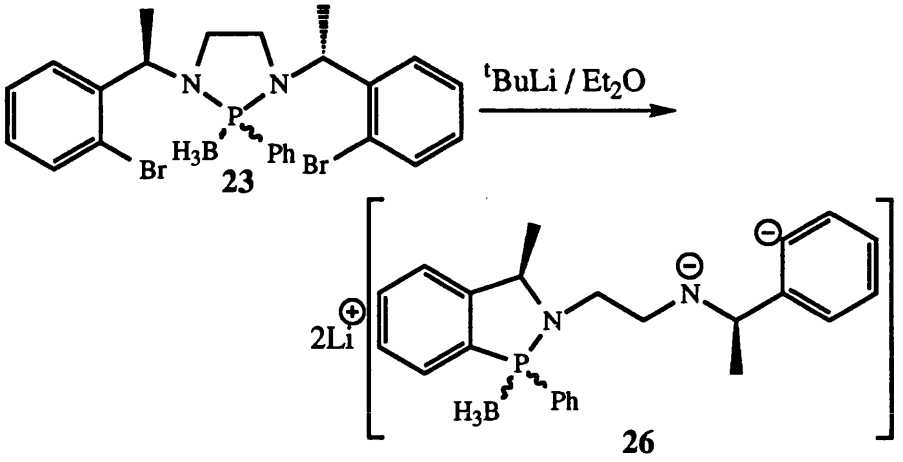



Figure 7.6.b



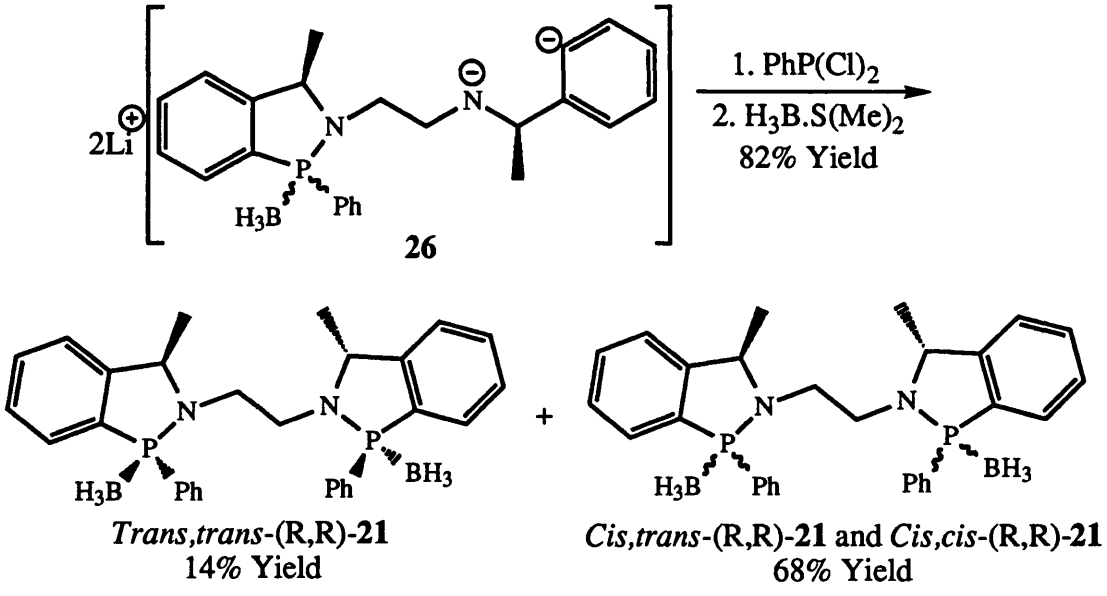

Scheme 7.6.c

The final reaction in the sequence proved to be exceptionally simple to carry out. Slow addition of 4.05 equivalents of $^{t}$BuLi to an ether *suspension*[48] of **23** at -70°C followed by stirring at -70°C for a further 15 minutes produces a very respectable yield of **26** (Scheme 7.6.d).




Scheme 7.6.d

This can be quenched with dichlorophenyl phosphine and the resultant phosphine may be borated in a very similar manner to **15** and **18** (Scheme 7.6.e).




Scheme 7.6.e

Unfortunately, no diastereoselectivity is observed so a statistical mixture of the *trans,trans*, the *cis,cis* and the *cis,trans* compounds are produced. However, column chromatography separated one of the $C_2$ symmetric compounds, assigned the *trans,trans* relative configuration (see section 7.7) from the other two diastereomers.

7.7 Solubility:

Having obtained X-rays of both *trans*-**15** and *trans*-**18** to confirm their relative stereochemistry it was hoped that X-ray quality crystals of the separated diastereomer of (R,R)-**21** would be forthcoming. This has not been possible because **21** is highly insoluble in virtually all solvents except DCM and chloroform. Any attempt at two solvent mixtures results in instant precipitation of **21** as a fine white powder.
Hence, assignment of the relative stereochemistry of **21** can only be based on $^{1}H$ NMR spectroscopy. The fact that it is a $C_2$ symmetric diastereomer that has been separated is evidenced by the extreme simplicity of the $^{1}H$ NMR spectra. There is only one doublet for the (α)-methyl and one signal, a quartet, for the proton attached to the (α)-methyl carbon. This still does not give any information about the relative stereochemistry of the heterocycle.
However, NMR does give a unique signal for each of the dihydrobenzazaphosphole-borane diastereomers isolated in this project via the proton attached to the (α)-methyl carbon (see section 7.7 and 4.3.b).
Given that the separated diastereomer of **21** has a quartet for the proton shown (see Figure 7.7), the inference is that this diastereomer of **21** is of *trans,trans* relative configuration.

Having made, fully characterised and separated a diastereomer of **21** screening was the next priority.

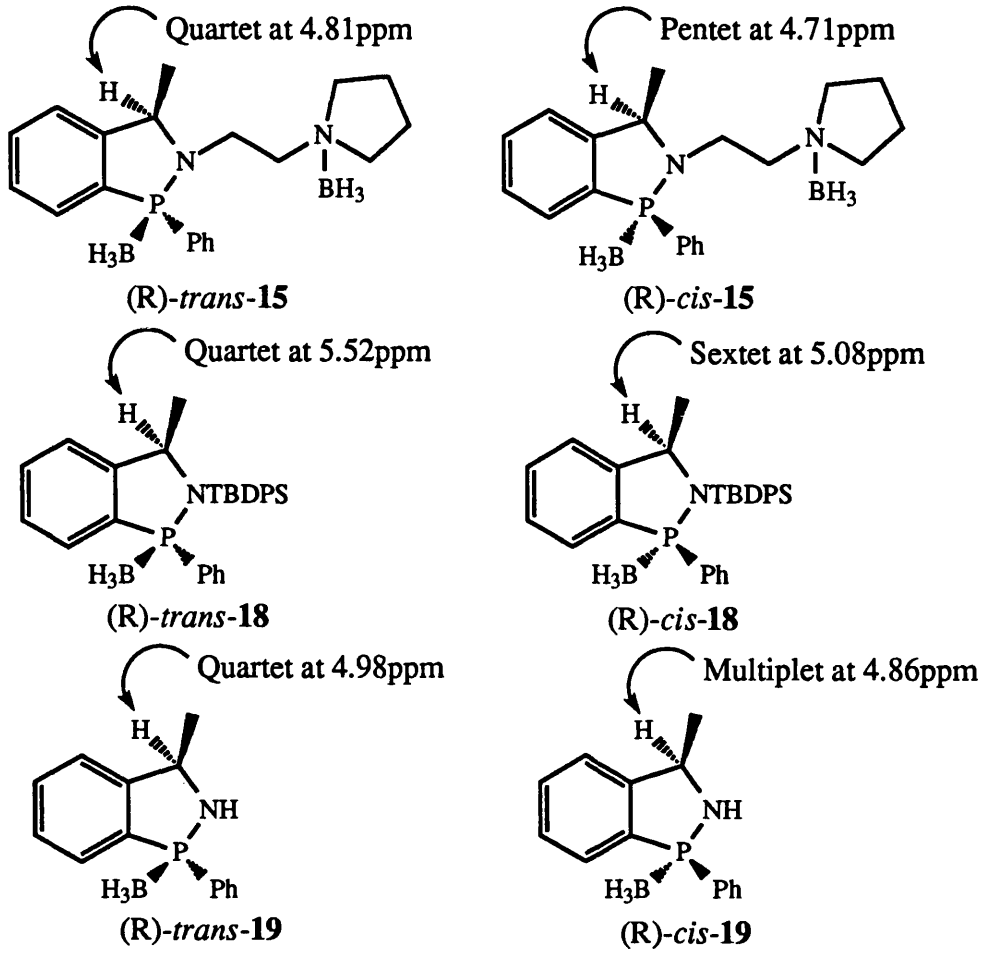
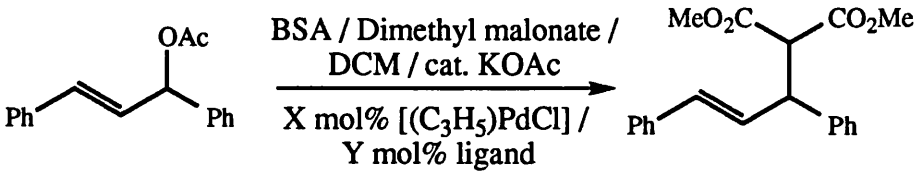

Quartet at 4.81ppm
Pentet at 4.71ppm
(R)-*trans*-**15**
(R)-*cis*-**15**
Quartet at 5.52ppm
Sextet at 5.08ppm
NTBDPS
(R)-*trans*-**18**
(R)-*cis*-**18**
Quartet at 4.98ppm
Multiplet at 4.86ppm
NH
(R)-*trans*-**19**
(R)-*cis*-**19**

Figure 7.7

# 8. Screening the Dimer

8.1 Allylic alkylation:

Several $C_2$ symmetric ligands[49] have been used in this reaction (see Scheme 8.1) with a fair amount of success. However, using the separated *trans,trans*-**21**[50] in this reaction under the same conditions as used for *trans*-**18** gave much poorer results (Table 8.1).




Scheme 8.1

Table 8.1

| Ligand | Mol% Pd | Mol% Ligand | Deboration Method | Yield | %ee | Configuration |
|---|---|---|---|---|---|---|
| (R)-**21** | 1 | 5 | Morpholine | 95 | 20 | R |
| (R)-**21** | 1 | 2.5 | Morpholine | 29 | 54 | R |

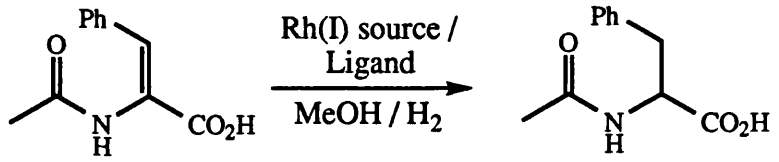
The reaction is not only much slower than that with **18** but it is also very difficult to use DABCO to deborate **21** because of the ligand's insolubility in solvents that facilitate the DABCO deboration reaction.[39] For this reason experiments using **21** in later sections of this thesis use the morpholine deboration methodology exclusively.

8.2 Hydrogenation:

**21** was originally conceived as a hydrogenation ligand in the mould of BINAP. When deborated and placed around a metal centre it would be predicted to show a similar 'propeller' arrangement of phenyl rings to BINAP, thus giving a highly chiral

environment in which reaction can take place (see Figure 8.2.b). This 'propeller' arrangement of phenyl rings has been cited as one of the main reasons that BINAP is such an effective ligand for such a wide range of enantioselective catalytic processes.[65] Virtually all hydrogenation ligands (see section 1.3) use a chiral scaffold to provide a 'propeller' arrangement of aryl / alkyl groups when coordinated to a metal centre.

The classic substrates[51] for catalytic asymmetric hydrogenation are N-acyl-(α)-aminoacrylates. These compounds are reduced to give N-protected-(α)-aminoacids (Scheme 8.2.a).




Scheme 8.2.a

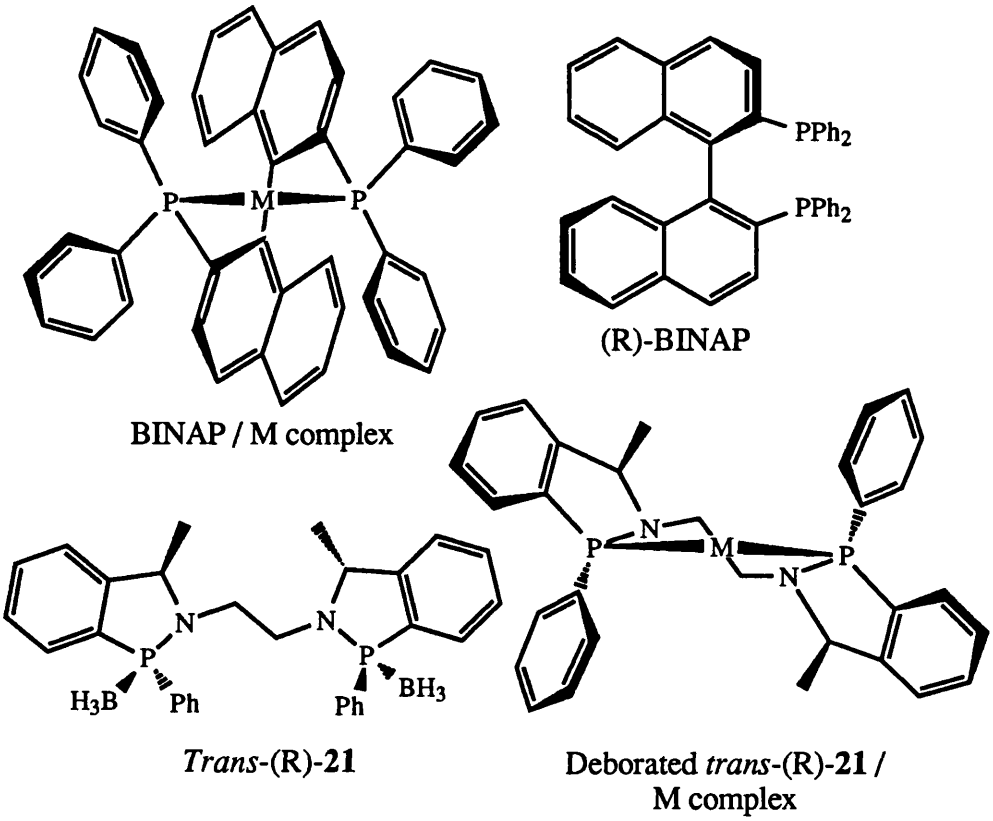
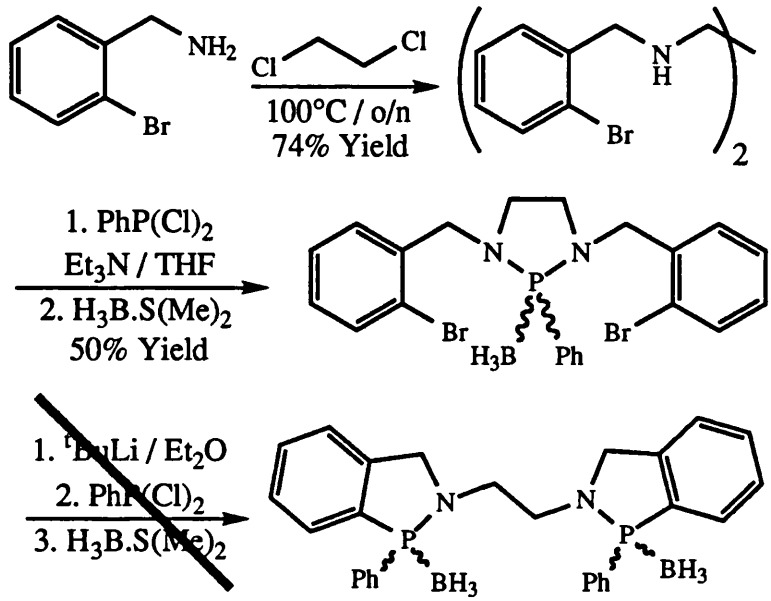


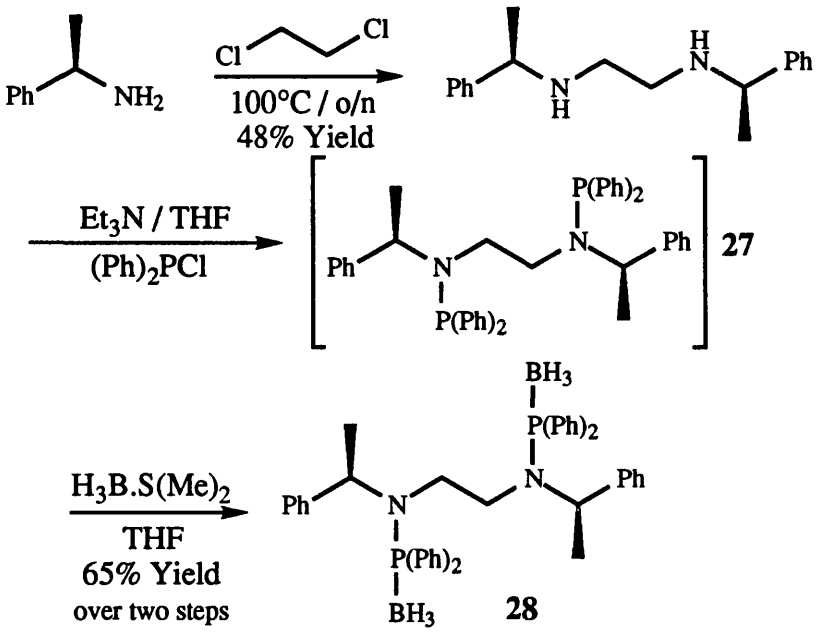

Figure 8.2.b

Initial trials of **21** in the reaction shown in Scheme 8.2.a gave no reduction. Rather than use precious **21** to develop this reaction a simple model system was needed. Initially, an analogue of **21** without the (α)-methyl (see Scheme 8.2.c) was proposed as the target. However, problems with benzylic deprotonation in the final step made alternatives more viable. This gave another example (see section 2.3.b) of the unexpectedly large effect that the (α)-methyl can have on the outcome of a reaction.



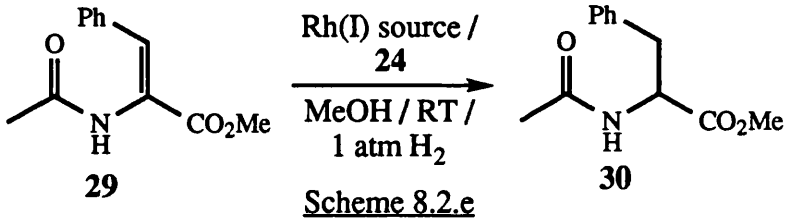

Scheme 8.2.c

One alternative was the previously reported[52] PNNP-type ligand, **27**, (see Scheme 8.2.d). This proved to be very easy to make, however, it was not isolated. Subsequent borane protection of the P(III) centres, **28**, gave a much closer analogue of **21** containing P-N *and* P-B bonds.




Scheme 8.2.d

Using similar deboration and complex formation procedures to those described in section 4.4 with $[(COD)RhCl]_2$ as the Rh(I) source the homogeneous hydrogenation of **29** (see Scheme 8.2.e) was attempted.




Scheme 8.2.e

Table 8.2

| Ligand | Mol% Rh | Mol% Ligand | Deboration Method | Yield | %ee[68] | Configuration |
|---|---|---|---|---|---|---|
| **28** | 10 | 12 | Morpholine | quant | 62 | S |
| **28** | 10 | 12 | Morpholine | quant | 60 | S |
| **28** | 10 | 12 | Morpholine | quant | 71 | S |
| **28** | 10 | 12 | Morpholine | quant | 77 | S |

At the 10mol% level of Rh(I) complex under 1 atm of hydrogen the reactions were complete in under half an hour.The last result in the table above (Table 8.2) is comparable with that observed by the group that first used **27** in this reduction.[53] Having refined the hydrogenation reaction to this point it was felt that **21** should be used in this reaction. However, with less than 50mg of **21** left synthesis of this compound became the main priority.

8.3 The Meerwein-Ponndorf-Verley reduction:

The synthesis of **21** was discussed in chapter 7. Although commercially available, the starting material used, **31**, (see Figure 8.3.a) is very expensive. This dictated a chiral synthesis and the obvious place to start was the chiral reduction of 2'-bromoacetophenone.

There are many literature methods of reducing prochiral ketones to give enantiomerically enriched alcohols[8]. The well known CBS reagents[54] suffer from extreme sensitivity to water giving variable results, various other borane reagents developed by Midland[55], Brown[56] and Masamune[57] are stoicheiometric and BINAP-Ru complexes[58] (see Figure 8.3.a) require extremely high pressures of hydrogen (>100 atm). One candidate that has not been heavily cited in the literature is the enantiomerically modified Meerwein-Ponndorf-Verley reduction, developed by Evans.[10]

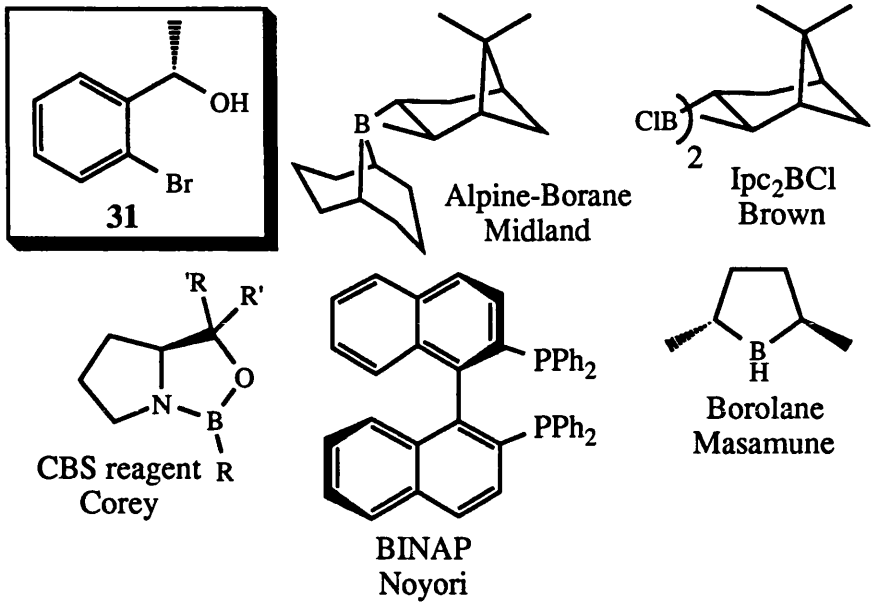
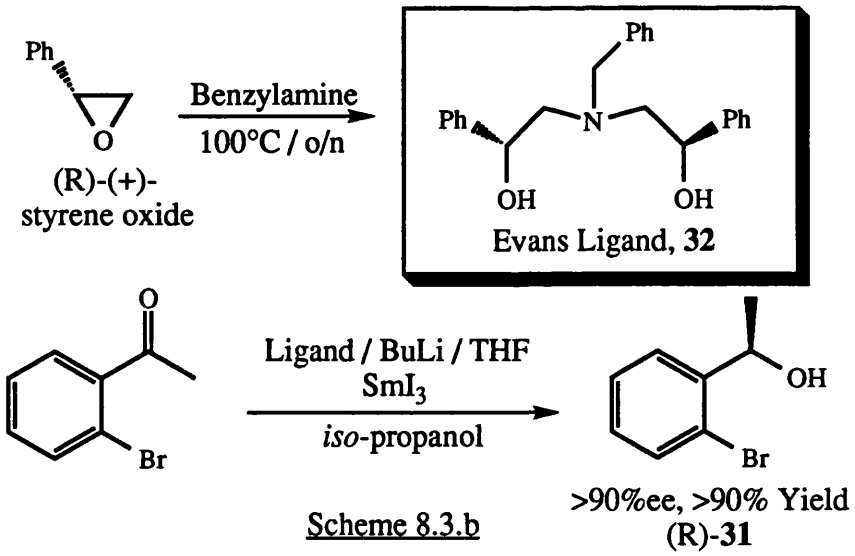



Figure 8.3.a - Asymmetric carbonyl reduction agents

This has the distinction of using *iso*-propanol as the stoicheiometric reducing agent and cheap, readily available enantiomerically pure styrene oxide as the originating source of chirality (see Scheme 8.3.b).




Scheme 8.3.b

Following a literature reference[10] ligand **32**, shown in Scheme 8.3.b, was prepared and used to reduce 2'-bromoacetophenone. This gave very promising results with

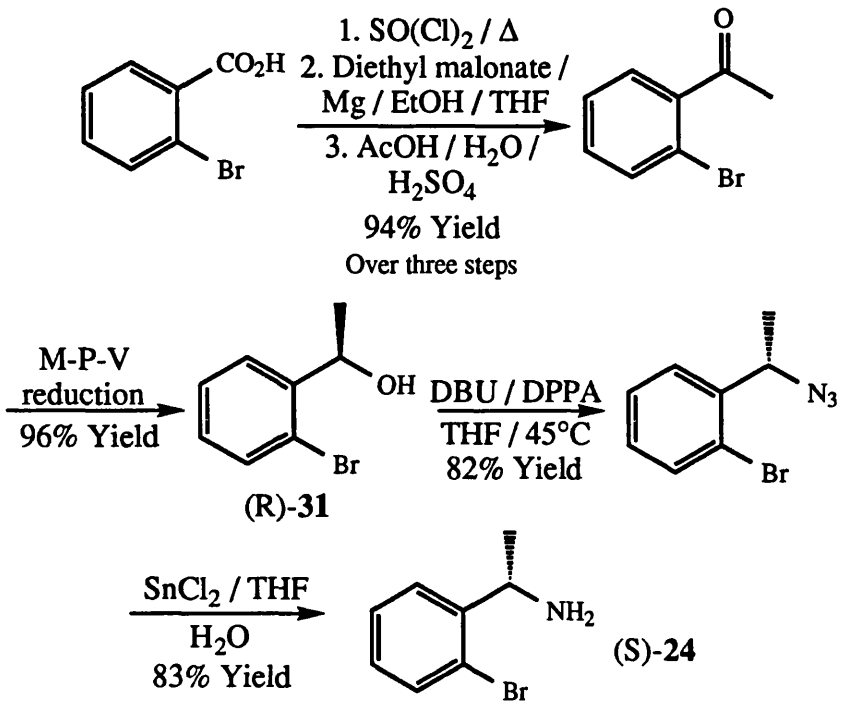
yields of greater than 90% and a minimum of 90%ee. However, the much cheaper (R)-styrene oxide derived ligand (R,R)-**32** leads to (R)-**31**, the antipode of the commercially available alcohol.

Since **31** is a crystalline solid, recrystallisation can be used to upgrade the material from >90%ee to >98%ee. With these results in hand, a large scale preparation of (S)-2-bromo-(α)-methyl benzylamine was undertaken (see Scheme 8.3.c).

Starting from 325g of 2-bromobenzoic acid[45] a total of 76g of highly enantiomerically enriched (>96%ee by HPLC)[47] (S)-2-bromo-(α)-methyl benzylamine was produced (see section 7.5), a yield of more than 23% over 5 steps. This amine was then used to produce (S,S)-**21** (see section 7.6).

Instead of reacting all of the **23** produced (69g, 19% yield from (S)-**31**) to give **21**, batches of **23** were reacted as fresh supplies of **21** were required. Typical total yields for the last step (**23** to **21**) were 70-80%.

With a quantity of the separated diastereomer of (S,S)-**21** in hand systematic screening of this material in the hydrogenation reaction was attempted.

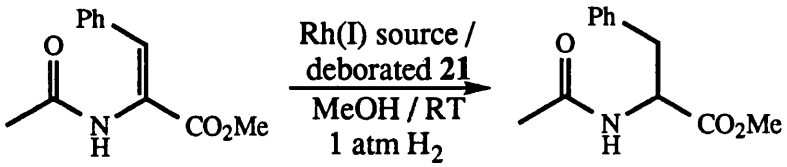

1. SO(Cl)2 / Δ
2. Diethyl malonate / Mg / EtOH / THF
3. AcOH / H2O / H2SO4
94% Yield
Over three steps
CO2H
Br
O
M-P-V reduction
96% Yield
OH
(R)-31
DBU / DPPA
THF / 45°C
82% Yield
N3
SnCl2 / THF
H2O
83% Yield
NH2
(S)-24

Scheme 8.3.c

# 9. Hydrogenation, Hydrosilylation and Heck reactions

## 9.1 Hydrogenation:

The separated diastereomer of (S,S)-**21** was tested using the standard hydrogenation screen shown in Scheme 9.1.




**29** Scheme 9.1.a **30**

Table 9.1

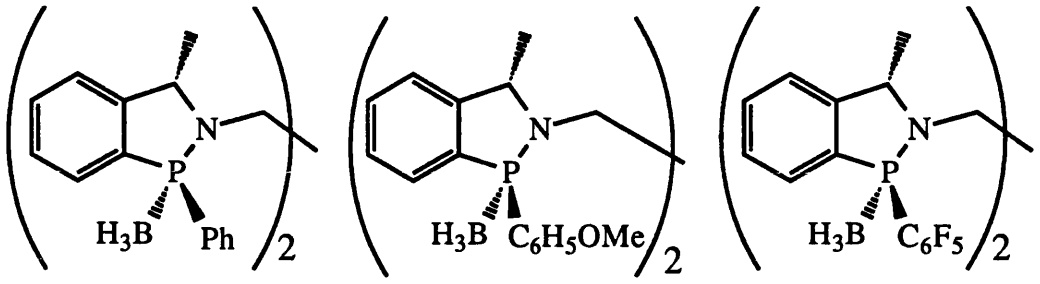
| Ligand | Mol% Rh | Mol% Ligand | Deboration Method | Yield | %ee[68] | Configuration |
|---|---|---|---|---|---|---|
| **21** | 10 | 12 | Morpholine | 50[a] | - | - |
| **21** | 10 | 12 | Morpholine | 50[a] | - | - |
| **21** | 10 | 12 | Morpholine | 94 | 33 | R |

a - Reaction only 50% complete, this product gave no reading on polarimetry.

In complete contrast to the above reaction using **28** (see section 8.2), ligand **21** gave very poor accelerations. The reaction only goes to completion at the 10mol% Rh(I) complex level over three days at 1 atm of hydrogen. There is some precedent for this low activity[60] if it is assumed that the nitrogen atom attached to each phosphorus atom in **21** acts to *reduce* electron density on phosphorus.

Unfortunately, the lack of time precludes the synthesis of the 4-methoxy, **33**, and pentafluorophenyl, **34**, derivatives shown in Scheme 9.1.b. These derivatives would

allow the testing of this hypothesis by altering the electron density on phosphorus in a known sense.



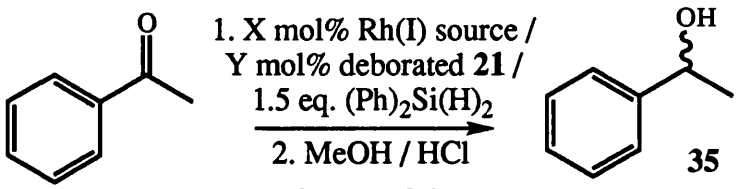

(S)-**21** (S)-**33** (S)-**34**

Figure 9.1.b

If this hypothesis is correct **33** should have a much higher activity, and **34** a much lower activity than **21** in the hydrogenation reaction above (Scheme 9.1.a).
Having discovered the low activity of **21** in the hydrogenation reaction other screens were looked at. The first to be considered was the hydrosilylation reaction (see section 1.4.a).

## 9.2 Hydrosilylation:

Other workers in the group[61] have developed a method for separating the two enantiomers of (α)-methyl benzyl alcohol, **35**, by chiral HPLC. Thus the reaction shown in Scheme 9.2.a was chosen as the initial screen.




Scheme 9.2.a

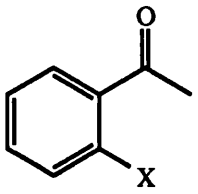
Table 9.2

| Ligand | Mol% Rh | Mol% Ligand | Temperature (°C) | Yield | %ee[69] | Configuration |
|---|---|---|---|---|---|---|
| **21** | 5 | 6 | 0 | 44 | 37 | S |
| **21** | 2.5 | 3 | 0 | 82 | 41 | S |
| **21** | 1.25 | 1.5 | 0 | quant. | 35 | S |

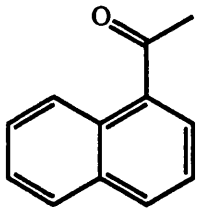
These results (Table 9.2) gave moderate encouragement. Apparently selectivity did not drop off to any large extent when lower mole percentages of Rh(I) complex were used and at low mole percentages the yields were high. However, the selectivities are not very large. In an effort to produce higher selectivity a series of experiments was carried out in which the atom in the 2-position on the aryl ring was altered (see Figure 9.2.b).

Table 9.3

| Substrate | Mol% Rh | Mol% Ligand | Temperature (°C) | Yield | %ee[62] | Configuration |
|---|---|---|---|---|---|---|
| **35** | 5 | 6 | 0 | 44 | 37 | S |
| **36** | 5 | 6 | 0 | 66 | 78 | S |
| **37** | 5 | 6 | 0 | 75 | 68 | S |
| **38** | 5 | 6 | 0 | 42 | - | - |
| **39** | 5 | 6 | 0 | 50 | 14 | S |




**35**, X = H
**36**, X = Cl
**37**, X = Br
**38**, X = I




**39**

Figure 9.2.b

In compounds **36-38** the halogen atom enables the compound to have 2-point binding to the Rh(I) centre. This is reflected in the much higher selectivities seen. However, compound **37** would be expected to give a higher selectivity than **36** because bromine is so much larger than chlorine if steric effects were working in concert with 2-point binding.

The fact that **37** gave a lower selectivity than **36** (Table 9.3) suggests that the strength of the 2-point binding is much more important than steric factors.

To test this theory compound **39**, which bears a large non-coordinating group, was reduced. This gave a very low selectivity confirming that 2-point binding is the major contributor to selectivity in this reaction.

Further reactions, varying the temperature (Table 9.4) using substrate **37** showed that this reaction does, as expected, give lower selectivities at higher temperature.

Table 9.4

| Substrate | Mol% Rh | Mol% Ligand | Temperature (°C) | Yield | %ee | Configuration |
|---|---|---|---|---|---|---|
| **37** | 5 | 6 | RT | 69 | 53 | S |
| **37** | 5 | 6 | 0 | 75 | 68 | S |

Another series of experiments using substrate **37** (Table 9.5) showed that this reaction gives lower selectivities when a lower concentration of Rh(I) complex is used mainly because of a longer reaction time, which allows an uncatalysed reaction pathway to compete.

Table 9.5

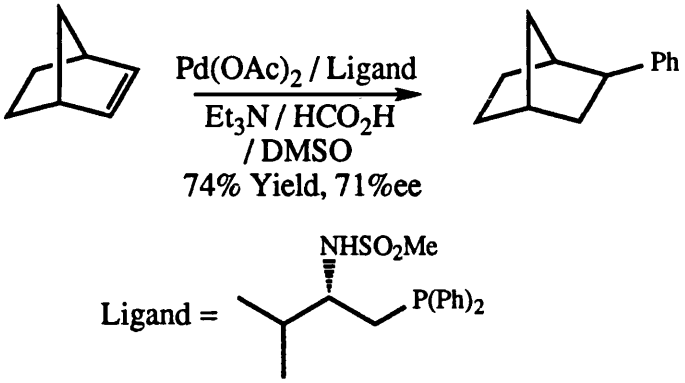
| Substrate | Mol% Rh | Mol% Ligand | Temperature (°C) | Yield | %ee | Time (hrs) |
|---|---|---|---|---|---|---|
| **37** | 5 | 6 | 0 | quant | 73 | 2 |
| **37** | 2.5 | 3 | 0 | 43 | 49 | 4 |
| **37** | 1.25 | 1.5 | 0 | 77 | 50 | o/n |

This suggests that the small amount of borane-morpholine complex present from the deboration of the ligand is acting as an achiral reducing agent in its own right (see section 5.2). There is a point at which the amount of borane-morpholine complex present ceases to make a significant difference to the final selectivity of the reaction. In the above case this point appears to be reached somewhere between 1.5 and 3 mol% ligand.

One further screen was briefly examined, an asymmetric variant on the Heck reaction (see section 1.4.c).

9.3 The 'Heck' reaction:

A recent reference[23] described the use of a bidentate ligand with electronically different donor atoms in the reaction shown in Scheme 9.3.




Scheme 9.3

At the 0.9mol% Pd level used the reaction took 20 hours at 65°C to go to completion. Following the procedure in the reference exactly gave the following results (Table 9.6).

Table 9.6

| Ligand | Mol% Pd | Mol% Ligand | Deboration Method | Yield | %ee[23] | Configuration[63] |
|---|---|---|---|---|---|---|
| **21** | 0.5 | 1.2 | Morpholine | 31 | 66 | - |
| **21** | 1 | 2.4 | Morpholine | 29 | 80 | - |

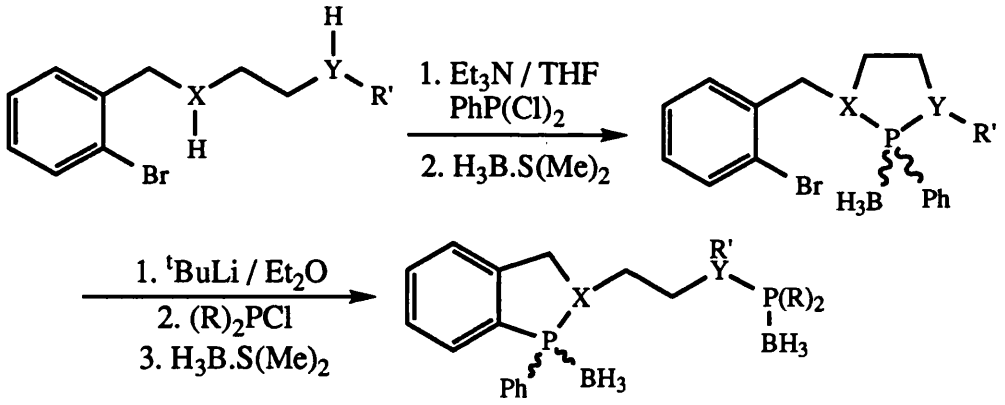
These ee values were measured by rotation. An HPLC method for separation of the enantiomers is being developed. The results above show that this reaction is an unusually good candidate for further development.

# 10. The Future

10.1 The dihydrobenzazaphosphole core:

Ligands containing the dihydrobenzazaphosphole core unit have been proved to be effective in several applications (see chapters 4,5,8 and 9). However, the most widely applicable ligand, the *di*phosphine **21**, cannot be made very efficiently because the last step in its synthesis involves the separation of three diastereomers, only two of which (*cis,cis* and *trans,trans*) are useful (see section 7.6). This information coupled with the emergence of several very successful diphosphine ligands that rely on electronic difference between each coordinating P(III) centre *as well as* steric bias (see section 1.4.b) suggests that *un*symmetrical diphosphine ligands have great potential.

One reaction that was developed during the synthesis of **21** allows a very flexible approach to unsymmetrical diphosphine ligands (see Scheme 10.1).




Scheme 10.1

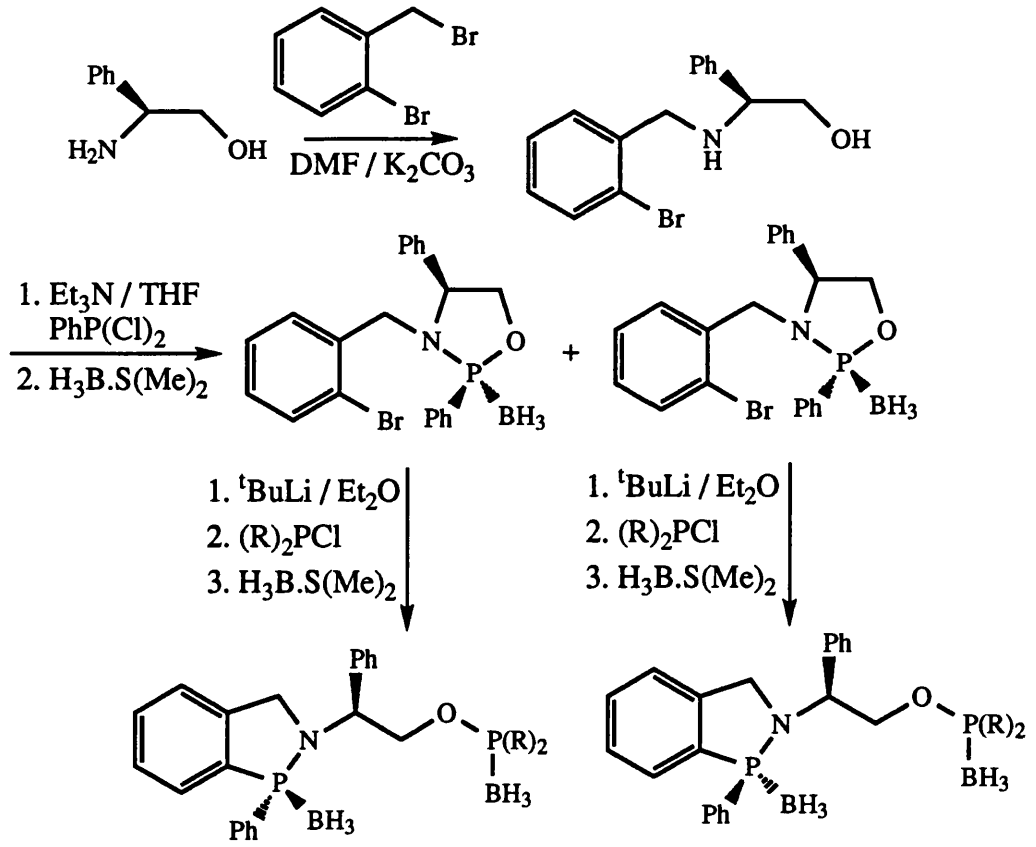
If X is nitrogen and Y is oxygen the backbone of this ligand is a (β)-amino-alcohol. Many chiral non-racemic (β)-amino-alcohols are available by simple reduction of (α)-aminoacids, thus giving a chiral backbone to the ligand allowing for possible separation of diastereomers at phosphorus. The second stage of the reaction shown in

Scheme 10.1 is known to give clean inversion at phosphorus so diastereomeric separation can be carried out in either of the last two steps.

10.2 Unsymmetrical diphosphine ligands:

Amino-alcohols are known to benzylate selectively on nitrogen.[64] This gives the following synthetic scheme (see Scheme 10.2).

One possible problem could occur in the third step of the synthesis. Competition between benzylic deprotonation and the halogen-exchange reaction (see section 8.2) would create many problems. Fortunately, the alkoxide anion generated in this reaction is a much better leaving group than the amine anion generated in the reaction in section 8.2. This leads to a very clean conversion giving extremely high yields. This piece of work is the subject of a patent application.




Scheme 10.2

This reaction gives the potential of very great variation, not only with many chiral amino-alcohol backbones to choose from, but also the nature of the substituents on the two P(III) centres. Fine tuning of both the steric *and* electronic properties of the ligand is thus possible.

The future of ligands containing the dihydrobenzazaphosphole moiety is thus very rich in possibilities. With luck and hard work some of these may turn out to be extremely effective ligands for catalytic asymmetric processes.

# Experimental

All air and moisture sensitive reactions were performed under an atmosphere of dry nitrogen or argon in thoroughly dried glassware.

Reagent purification:

TMEDA, morpholine and $Et_3N$ were distilled from $CaH_2$ before use. DCM was distilled from $P_2O_5$ and stored over 3Å molecular sieves. MeOH was distilled from, and stored over, 3Å molecular sieves. Acetonitrile was freshly distilled from $P_2O_5$. DABCO was recrystallised from hexane and stored under Ar.

Petrol refers to the fraction boiling in the range 60-80°C. Bromoacetylbromide, pyrollidine, petrol, and $PhP(Cl)_2$ were all distilled before use. THF, $Et_2O$ and hexane were all freshly distilled from sodium or potassium-benzophenone ketyl. Ethyl acetate was distilled from $K_2CO_3$.

Alkyl lithium reagents were titrated using the method of Juaristi *et al*[66].

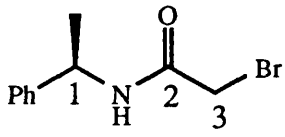
Spectral data:

$^1H$ NMR spectra were recorded in $CDCl_3$ solution on a Jeol GX270FT spectrometer at 270MHz, unless otherwise stated. $^{13}C$ NMR spectra were recorded on a Jeol GX270FT instrument operating at 67.8MHz unless otherwise stated.

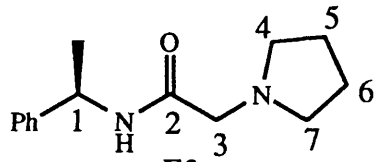
Mass spectra were recorded on a VG analytical 7070E instrument. Infra-red spectra were recorded on a Perkin-Elmer 1310FT spectrometer.

Microanalysis was performed at Bath University.

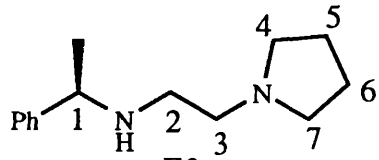
The atom and compound numbers used in the experimental section refer to the diagrams shown on the next page.



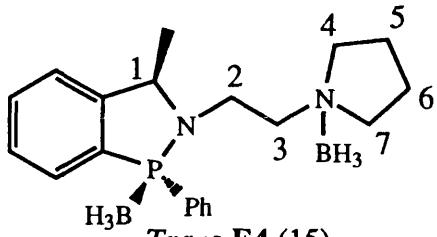
**E1**



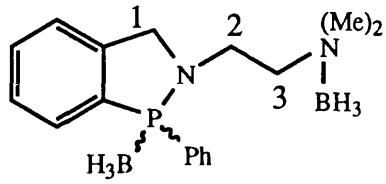
**E2**



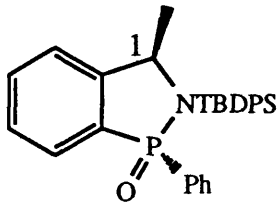
**E3**



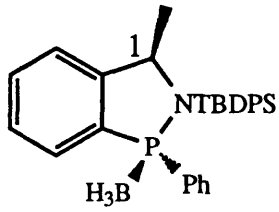
*Trans*-**E4** (15)



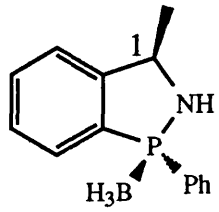
**E5**



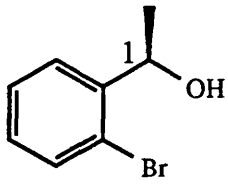
*Trans*-**E6** (17)



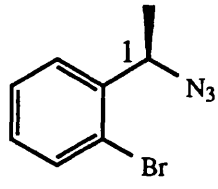
*Trans*-**E7** (18)



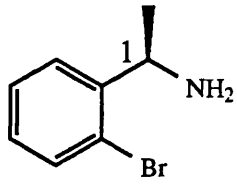
*Trans*-**E8** (19)



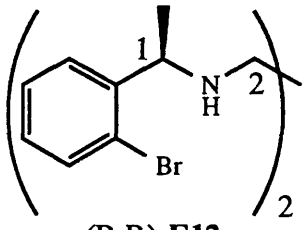
(R)-**E9** (31)



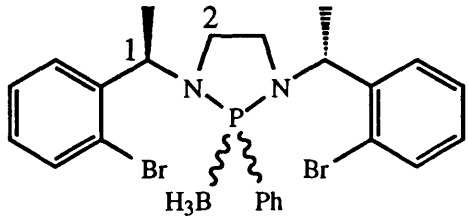
(R)-**E10**



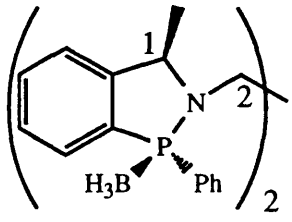
(R)-**E11** (24)



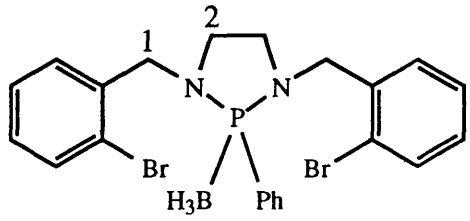
(R,R)-**E12**



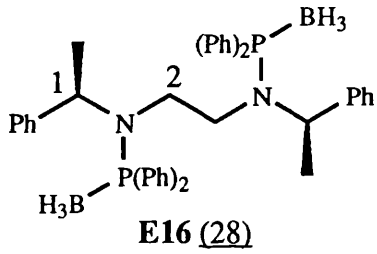
(R,R)-**E13** (23)



*Trans,trans*-(R,R)-**E14** (21)



**E15**



**E16** (28)

## E1 - [N-bromoacetyl]-(R)-(α)-methylbenzylamine:

To a stirred solution of (R)-(α)-methylbenzylamine (40.0g, 330.09mmol, 1eq.) and $Et_3N$ (35.07g, 346.59mmol, 1.05eq.) dissolved in dry DCM (500ml) cooled to -70°C was added dropwise a solution of bromoacetylbromide (66.63g, 330.09mmol, 1eq.) in dry DCM (100ml). The temperature was kept below -65°C throughout the addition. The resultant solution was stirred at -70°C for 5 minutes and quenched by rapid addition of 2M HCl (100ml) by syringe. The organic phase was washed with 2M HCl (500ml), sat. $Na_2CO_3$ (500ml), dried with $MgSO_4$, filtered and concentrated under reduced pressure. The white solid product was immediately recrystallised from DCM/hexane to give **E1** as a white crystalline solid (59.79g, 75%).

mp. 104°C (from DCM/hexane); $[\alpha]_D^{17}$ = +19.6° (c 0.598, DCM); (Found: C, 49.7; H, 4.98; N, 5.72. $C_{10}H_{12}NOBr$ requires: C, 49.60; H, 5.00; N, 5.79%); $\nu_{max}$ (nujol)/$cm^{-1}$ 3263.0, 1646.4; $\delta_H$ 1.52(3H, d, J = 7.0Hz, $C_1$-Me), 3.83(2H, m, $C_3$-$CH_2$), 5.09(1H, p, J = 7.3Hz, $C_1$-H), 6.85(1H, br s, NH), 7.32(5H, m, Ph-H); $\delta_C$ 21.54, 29.13, 49.46, 125.95, 127.47, 128.64, 142.49, 164.48; m/z 162(100%), 106(54)

## E2 - [N-(2-pyrrolidyl)-acetyl]-(R)-(α)-methylbenzylamine:

To a stirred solution/suspension of [N-bromoacetyl]-(R)-(α)-methylbenzylamine (72.36g, 298.86mmol, 1eq.) and $Et_3N$ (30.24g, 298.86mmol, 1eq.) in dry DCM (300ml) at 0°C was added dropwise pyrollidine (22.32g, 313.80mmol, 1.05eq.). The resultant solution was stirred at room temperature for 1 hour, poured into $H_2O$ (300ml) and extracted with 15% HCl (3 x 250ml). The acid extract was basified with 30% NaOH to pH >12, extracted with DCM (4 x 250ml), dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. The resulting solid was triturated with $Et_2O$ and filtered off to give **E2** as an off-white solid (59.89g, 86%).

mp. 109-110°C (from DCM/hexane); $[\alpha]_D^{20}$ = + 3.97° (c 2.08, DCM); (Found: C, 72.3; H, 8.92; N, 12.3. $C_{14}H_{20}N_2O$ requires: C, 72.37; H, 8.68; N, 12.06%); $\nu_{max}$

(nujol)/$cm^{-1}$ 3323.4, 1646.9; $\delta_H$ 1.50(3H, d, J = 7.0Hz, $C_1$-Me), 1.78(4H, m, $C_5$, $C_6$-$CH_2$), 2.58(4H, m, $C_4$, $C_7$-$CH_2$), 3.15(2H, m, $C_3$-$CH_2$), 5.18(1H, p, J = 7.0Hz, $C_1$-H), 7.32(5H, m, Ph-H), 7.37(1H, br s, NH); $\delta_C$ 21.70, 23.68, 47.65, 54.23, 59.10, 125.78, 126.89, 128.31, 143.14, 169.57; m/z 84(100%)

## E3 - [N-(2-pyrrolidyl)-ethyl]-(R)-(α)-methylbenzylamine (14):

To a vigorously stirred suspension of $LiAlH_4$ (19.51g, 515.58mmol, 2eq.) in dry THF (500ml) was added dropwise a solution of [N-(2-pyrrolidyl)-acetyl]-(R)-(α)-methylbenzylamine (59.89g, 257.74mmol, 1eq.) in dry THF (100ml). The resultant suspension was heated at reflux overnight, allowed to cool and 20ml $H_2O$ was added dropwise, followed by 20ml 15% NaOH and 60ml $H_2O$. The resultant was filtered, concentrated under reduced pressure, redissolved in $Et_2O$ (500ml), dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. The slightly green oil produced was dissolved in dry $Et_2O$ (300ml) and saturated with HCl gas, solvent was removed under reduced pressure and the solid residue was recrystallised from $^iPrOH$ to give an off-white solid. This solid was dissolved in $H_2O$ (100ml) and basified with 30% NaOH, extracted with $Et_2O$ (4 x 100ml), dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. Distillation gave **E3** as a colourless oil (24.31g, 43%).

bp. 98-100°C / 0.2mmHg; $[\alpha]_D^{20}$ = + 41.2° (c 2.021, DCM); (Found: C, 77.0; H, 10.4; N, 13.0. $C_{14}H_{22}N_2$ requires: C, 77.0; H, 10.2; N, 12.8%); $\nu_{max}$ (neat)/$cm^{-1}$ 3310.1, 1681.9; $\delta_H$ 1.36(3H, d, J = 6.6Hz, $C_1$-Me), 1.73(4H, s, $C_5$, $C_6$-$CH_2$), 2.41(4H, m, $C_4$, $C_7$-$CH_2$), 2.57(4H, m, $C_2$, $C_3$-$CH_2$), 3.74(1H, q, J = 6.6Hz, $C_1$-H), 7.30(5H, m, Ph-H); $\delta_C$ 23.06, 24.07, 46.12, 53.71, 55.66, 58.19, 126.14, 126.33, 127.92, 145.54; m/z 219(78%), 105(18), 84(100)

## E4 - [N-(2-pyrrolidyl)-ethyl]-(R)-dihydrobenzazaphosphole diborane complex (*trans*-15 and *cis*-15):

To a solution of [N-(2-pyrrolidyl)-ethyl]-(R)-(α)-methylbenzylamine (0.5g, 2.29mmol, 1eq.) and TMEDA (0.29g, 2.52mmol, 1.1eq.) in dry $Et_2O$ (0.5ml) cooled to -70°C was added dropwise n-BuLi (2.10ml, 5.04mmol, 2.4M, 2.2eq.). The resulting solution was allowed to reach room temperature and stirred at room temperature overnight. The bright orange solution was diluted with dry $Et_2O$ (10ml), cooled to -70°C and $PhP(Cl)_2$ (0.61g, 3.44mmol, 1.5eq.) added dropwise. The resulting yellow suspension was stirred at -70°C for 1 hour and at room temperature for 2 hours. Borane-dimethyl sulphide complex (0.73g, 9.62mmol, 4.2eq.) was added dropwise and the resulting thick yellow suspension was stirred at room temperature for 1 hour. It was then poured into saturated $NaHCO_3$ (50ml), extracted with DCM (4 x 50ml), dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. Flash chromatography (gradient elution: 0-25% EtOAc in petrol) gave a colourless gum (0.60g, 74%). Further flash chromatrography (gradient elution: 15-30% EtOAc in petrol) gave the less polar diastereomer, *cis*-**15**, as a colourless gum (36% yield) and the more polar diastereomer, *trans*-**15**, as a white crystalline solid (38% yield). The more polar diastereomer, *trans*-**15** (**E4**), was recrystallised from DCM / hexane.

Data for *trans*-**15**:

mp. 120-121°C; $[\alpha]_D^{20}$ = -210.1° (c 1.16, DCM); $\nu_{max}$ (nujol)/$cm^{-1}$ 2613.7, 2366.9, 2238.0, 1459.1, 1184.7; $\delta_H$ 0.2-2.2 (6H, br m, $BH_3$), 1.59 (3H, d, J = 6.2Hz, $C_1$-Me), 1.83(2H, br m, $C_5$, $C_6$-$CH_2$), 2.10 (2H, br m, $C_5$, $C_6$-$CH_2$), 2.75(2H, br m, $C_3$, $C_4$, $C_7$-$CH_2$), 3.13(2H, br m, $C_3$, $C_4$, $C_7$-$CH_2$), 3.35(1H, br m, $C_2$-$CH_2$), 3.65(1H, br m, $C_2$-$CH_2$), 4.81(1H, q, J = 6.2Hz, $C_1$-H), 7.42(9H, m, Ph-H); $\delta_C$ 21.44, 21.51, 22.27, 22.67, 39.69, 60.88, 62.44, 62.83, 63.87, 123.27, 123.37, 128.35, 128.53, 128.70, 128.83, 131.62, 131.66, 131.69, 131.83, 131.88, 131.91, 148.07, 148.16; $\delta_P$ 75.3(d, J = 81.0Hz); $\delta_B$ -10, -35 / -36; m/z 337(100%), 325(18), 84(18); X-ray data see Appendix

Data for *cis*-**15**:

$[\alpha]_D^{22}$ = +160.5° (c 1.26, DCM); $\nu_{max}$ (nujol)/$cm^{-1}$ 2613.7, 2366.9, 2238.0, 1459.1, 1184.7; $\delta_H$ 0.2-2.2 (6H, br m, $BH_3$), 1.61 (3H, d, J = 6.4Hz, $C_1$-Me), 1.85(2H, br m, $C_5$, $C_6$-$CH_2$), 2.09 (2H, br m, $C_5$, $C_6$-$CH_2$), 2.75(1H, br m, $C_3$, $C_4$, $C_7$-$CH_2$), 2.96(1H, br m, $C_3$, $C_4$, $C_7$-$CH_2$), 3.14(2H, br m, $C_3$, $C_4$, $C_7$-$CH_2$), 3.45(1H, br m, $C_2$-$CH_2$), 3.80(1H, br m, $C_2$-$CH_2$), 4.71(1H, q, J = 6.4Hz, $C_1$-H), 7.0-8.0(9H, m, Ph-H); $\delta_C$ 21.15, 22.02, 22.35, 38.99, 39.14, 60.59, 60.95, 61.63, 62.60, 123.12, 123.22, 127.83, 128.05, 128.31, 128.44, 130.88, 131.04, 131.17, 131.36, 147.51, 147.64

## E5 - [(2-dimethylamino)-ethyl]-dihydrobenzazaphosphole diborane complex:

To a solution of N-benzyl-N',N'-dimethylethylenediamine (10.0g, 56.09mmol, 1eq.) and TMEDA (7.17g, 61.70mmol, 1.1eq.) in dry $Et_2O$ (2ml) cooled to -70°C was added dropwise n-BuLi (51.42ml, 123.40mmol, 2.4M, 2.2eq.). The resulting solution was allowed to reach room temperature and stirred at room temperature overnight. The bright orange solution was diluted with dry $Et_2O$ (100ml), cooled to -70°C and $PhP(Cl)_2$ (15.06g, 84.14mmol, 1.5eq.) added dropwise. The resulting yellow suspension was stirred at -70°C for 1 hour and at room temperature for 2 hours. Borane-dimethyl sulphide complex (17.90g, 235.58mmol, 4.2eq.) was added dropwise and the resulting thick yellow suspension was stirred at room temperature for 1 hour. It was then poured into saturated $NaHCO_3$ (250ml), extracted with DCM (4 x 100ml), dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. Flash chromatography (gradient elution: 0-25% EtOAc in petrol) gave **E5** as a colourless gum, which later solidified (12.47g, 71%).

mp. 108-110°C (from EtOAc); (Found: C, 65.4; H, 8.91; N, 9.04. $C_{17}H_{27}N_2BP$ requires: C, 65.44; H, 8.72; N, 8.98%); $\nu_{max}$ (nujol)/$cm^{-1}$ 3209.9, 2940.2, 2357.6, 2072.2, 1988.3, 1895.8, 1818.2, 1705.9, 1589.6, 1455.6; $\delta_H$ 0.88-1.60(3H, br m,

$BH_3$), 2.57(3H, s, $N(Me)_2$), 2.62(3H, s, $N(Me)_2$), 2.90 (2H, m, $C_3$-$CH_2$), 3.5(2H, m, $C_2$-$CH_2$), 4.60(2H, m, $C_1$-$CH_2$), 7.2-7.6(9H, m, Ph-H); $\delta_C$ 41.1, 51.3, 52.8, 57.0, 62.0, 123.2, 128.4, 131.3; m/z 218(21%), 110(21), 86(65), 84(100), 43(29), 28(38)

## E6 - *Trans*-(R)-(-)-N-(*Tert*-butyldiphenylsilyl)-dihydrobenzazaphosphole oxide:[42]

TBDPS protected (R)-(α)-methylbenzylamine (2.0g, 5.56mmol, 1eq.)[40] was dissolved in dry $Et_2O$ (0.5ml) and TMEDA (0.71g, 6.12mmol, 1.1eq.) added. The resultant solution was cooled to -70°C and n-BuLi (4.89ml, 12.23mmol, 2.5M, 2.2eq.) added dropwise. The solid precipitate formed was redissolved by gentle heating using a heat-gun. After stirring at room temperature over-night the solution was cooled to -70°C and dry $Et_2O$ added (11ml). Phenylphosphinyldichloride (1.19g, 6.12mmol, 1.1eq.) was added slowly dropwise. The resulting slurry was stirred at -70°C for 1 hour and at room temperature for 1 hour.

The viscous yellow slurry was poured into saturated $NaHCO_3$ and extracted with DCM (4 x 50ml), dried over $Na_2SO_4$, filtered and concentrated under reduced pressure. Flash chromatography (gradient elution: 30-50% EtOAc in petrol) gave **E6** as a white solid (1.00g, 37%). This material was shown to be identical to an authentic sample of **E6** by $^1H$ NMR, polarimetry and TLC.

## E7 - *Trans*-(R)-(-)-(N-*Tert*-butyldiphenylsilyl)-dihydrobenzazaphosphole borane complex (*trans*-18):[67]

$Et_3N$ (1.13g, 11.21mmol, 6eq.) was added, dropwise over 1 minute, to a stirred solution of trichlorosilane (1.27g, 9.34mmol, 5eq.) in dry toluene (7.5ml) cooled in an ice-bath. The resultant solution was heated to 70°C and *trans*-(R)-(-)-N-(*Tert*-butyldiphenylsilyl)-dihydrobenzazaphosphole oxide (0.90g, 1.87mmol, 1eq.) was added in one portion. The solution was stirred at 70°C for 3.25 hours, cooled in an ice-

bath and borane:dimethyl sulphide complex (1.01g, 13.27mmol, 7.1eq.) added dropwise. This solution was stirred at room temperature for 0.75 hours, poured into saturated $NaHCO_3$, extracted with EtOAc (3 x 50ml), dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. Flash chromatography (5% EtOAc in petrol) gave **E7** as a white solid which was recrystallised from DCM / hexane (0.31g, 35%).

mp. 191-193°C (DCM / hexane); $[\alpha]_D^{20}$ = -405.3° (c 0.246, DCM); (Found: C, 74.9; H, 7.46; N, 3.08. $C_{30}H_{35}NSiPB$ requires: C, 75.15; H, 7.36; N, 2.92%); $\nu_{max}$ (nujol)/$cm^{-1}$ 2721.4, 2418.9, 2363.0, 2314.5, 2239.5, 1588.4, 1463.8, 1427.5, 1396.4, 1376.0; $\delta_H$ 0.2-2.0(3H, br m, $BH_3$), 1.26(9H, s, $^tBu$), 1.44(3H, d, J = 6.6Hz, $C_1$-Me), 5.52(1H, m, $C_1$-CH), 6.92(4H, m, Ph-H), 7.15-7.6(13H, m, Ph-H), 8.01(3H, m, Ph-H); $\delta_C$ 20.11, 27.67, 29.69, 65.52, 122.30, 122.43, 126.90, 127.58, 127.76, 127.89, 128.26, 128.39, 128.46, 128.54, 129.43, 129.50, 130.91, 130.94, 132.16, 132.43, 132.59, 133.46, 135.14, 136.42, 136.79, 137.43, 137.51, 148.47; $\delta_P$ 84.19 (d, J = 70.5Hz); m/z (NOBA matrix) 481.2(7%), 480.2(19), 479.2(37), 478.2(100), 477.2(30)

## E8 - *Trans*-(R)-(-)-benzazaphosphole borane complex (*trans*-19):

*Trans*-(R)-(-)-(N-*Tert*-butyldiphenylsilyl)-dihydrobenzazaphosphole borane complex (0.5g, 1.04mmol, 1eq.) was dissolved in dry THF (10ml) and TBAF (1.04ml, 1.15mmol, 1.1eq.) added. The resultant solution was stirred at RT for 2 hours, poured into saturated $NH_4Cl$ and extracted with EtOAc (4 x 50ml). The organic extract was dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. Flash chromatography (gradient elution: 10-15% EtOAc in petrol) gave **E8** as a colourless oil (245mg, 98%).

mp. 202-203°C (DCM / hexane); $[\alpha]_D^{20}$ = -62.7° (c 0.95, chloroform); (Found: C, 69.7; H, 7.18; N, 5.68. $C_{14}H_{17}NPB$ requires: C, 69.75; H, 7.11; N, 5.81%); $\delta_H$ 0.2-1.8(3H, br q, J = 45Hz, $BH_3$), 1.59(3H, d, J = 6.4Hz, $C_1$-Me), 2.42(1H, br d, J

= 17.4Hz, NH), 4.98(1H, q, J = 6.4Hz, $C_1$-CH), 7.3-7.75(9H, m, Ph-H); $\delta_C$ 24.28, 59.45, 59.52, 122.96, 123.07, 128.25, 128.35, 128.39, 128.54, 130.57, 130.73, 131.23, 131.72, 135.19, 135.90, 148.65, 148.78; m/z 227(73%), 212(43), 150(100)

## E9 - (R)-(α)-methylbenzyl alcohol (31):[10]

The samarium complex was prepared using the conditions described in the paper referenced. To a solution of 2 mole% of this complex was added dry, degassed *iso*-propanol (601g, 10moles, 25eq.) followed by 2'-bromoacetophenone (79.62g, 400mmol, 1eq.). The resulting mixture was stirred at RT for 3 days. Saturated sodium potassium tartrate (20ml) was added and the resulting suspension was stirred vigorously at RT for 15 minutes. *Iso*-propanol, THF and acetone were removed under reduced pressure and the resulting suspension was extracted with EtOAc (5 x 200ml), the organic extract was dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. Trituration with $Et_2O$ allowed collection of the ligand HCl salt by filtration and concentration under reduced pressure of the resulting organic solution gave a yellow oil. Flash chromatography (gradient elution: 15-25% EtOAc in petrol) gave a slightly yellow oil which was crystallised from hexane to give **E9** as white crystals (59.52g, 74%). This material was shown to be identical to an authentic sample of **E9** by $^1H$ NMR and polarimetry.

$\delta_H$ 1.47(3H, d, J = 6.4Hz, $C_1$-Me), 2.16(1H, br s, OH), 5.23(1H, q, J = 6.4Hz, $C_1$-CH), 7.12(1H, dt, J = 1.7, 7.7Hz, Ph-H), 7.34(1H, dt, J = 1.1, 7.5Hz, Ph-H), 7.51(1H, dd, J = 1.3, 8.0Hz, Ph-H), 7.58(1H, dd, J = 1.8, 7.8Hz, Ph-H); $[\alpha]_D^{22}$ = +58.2° (c 1.15, chloroform)[59]

## E10 - (R)-2-bromo-(α)-methylbenzylazide:[46]

(S)-2-bromo-(α)-methylbenzyl alcohol (5.0g, 24.87mmol, 1eq.) was dissolved in dry THF (40ml) and diphenylphosphoryl azide (8.21g, 29.84mmol, 1.2eq.) was added. The resultant mixture was cooled in an ice-bath and 1,8-diazabicyclo[5, 4, 0]undec-7-

ene (4.54g, 29.84mmol, 1.2eq.) added dropwise. Stirring was continued at 0°C for 1 hour and at RT overnight. The mixture was then warmed to 40°C for 3 hours, allowed to reach RT and diluted with $Et_2O$ and water. The aqueous phase was extracted with $Et_2O$ (4 x 100ml) and the $Et_2O$ extract was washed with 5N HCl (1 x 200ml). The aqueous phase was back extracted with $Et_2O$ (2 x 100ml), the combined organics were dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. Flash chromatography (5% EtOAc in petrol) gave **E10** as a mobile, colourless oil (4.65g, 83%).

bp. 115°C / 0.5mmHg; $[\alpha]_D^{20}$ = +19.4° (c 3.465, DCM); (Found: C, 42.9; H, 3.63; N, 18.4. $C_8H_8N_3Br$ requires: C, 42.5; H, 3.57; N, 18.59%); $\nu_{max}$ (neat)/$cm^{-1}$ 3327.0, 3062.5, 2980.4, 2931.9, 2483.2, 2092.3; $\delta_H$ 1.51(3H, d, J = 6.6Hz, $C_1$-Me), 5.11(1H, q, J = 6.8Hz, $C_1$-CH), 7.16(1H, td, J = 1.8, 7.4Hz, Ph-H), 7.31(1H, t, J = 1.2, 7.8Hz, Ph-H), 7.44(1H, dd, J = 1.8, 7.8Hz, Ph-H), 7.56(1H, dd, J = 1.2, 7.9Hz, Ph-H); $\delta_C$ 20.74, 59.76, 122.62, 127.26, 127.94, 129.24, 132.92, 140.23; m/z 228(2%), 227(10), 226(2), 225(11), 199(38), 198(48), 197(40), 196(46), 185(96), 184(42), 183(100), 182(38), 158(5), 157(24), 156(6), 155(25)

## E11 - (R)-2-bromo-(α)-methylbenzylamine (24):[45]

(R)-2-bromo-(α)-methylbenzylazide (4.64g, 20.54mmol, 1eq.) was dissolved in THF (50ml) and cooled in an ice-bath. A solution of $SnCl_2.2H_2O$ (13.90g, 61.62mmol, 3eq.) in water (60ml) was added dropwise. The ice-bath was allowed to melt as the solution was stirred overnight. The resultant opaque mixture was diluted with $Et_2O$ and 5N HCl and extracted with 5N HCl (3 x 100ml). The aqueous layer was basified to pH 10 with concentrated aqueous ammonia and extracted with $Et_2O$ (3 x 100ml). The organic extract was dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. The resultant yellowish oil was distilled under reduced pressure to give **E11** as a colourless mobile oil (3.82g, 93%). This material was shown to be identical to a sample of *rac*-**E11**, produced by a Leuckart amination of 2'-bromoacetophenone[45], by

$^1H$ NMR and boiling point. The enantiomeric excess of (R)-**E11** was measured by HPLC.[47]

bp. 110°C / 20mmHg; $\delta_H$ 1.38(3H, d, J = 6.6Hz, $C_1$-Me), 1.55(2H, br s, $NH_2$), 4.50(1H, q, J = 6.6Hz, $C_1$-CH), 7.08(1H, dt, J = 1.7, 7.4Hz, Ph-H), 7.31(1H, dt, J = 1.3, 3.7Hz, Ph-H), 7.52(2H, td, J = 1.2, 7.9Hz, Ph-H)

## E12 - (R)-2-bromo-(α)-methylbenzylamine ethyl dimer:[44]

(R)-2-bromo-(α)-methylbenzylamine (6.0g, 29.99mmol, 1eq.) neat was heated to 100°C and 1, 2-dichloroethane (1.19g, 12.00mmol, 0.4eq.) was added dropwise by syringe-pump over two hours. The resulting mixture was stirred at 100°C overnight, allowed to cool to RT and partitioned between 40% NaOH and $Et_2O$. The aqueous layer was extracted with $Et_2O$ (3 x 20ml), the organic layer was dried over $Na_2SO_4$ / NaOH, filtered and concentrated under reduced pressure. Distillation of the orange oil (105°C / 10mmHg) recovered unreacted starting material (4.33g, 72%) and distillation of the residue (165°C / 0.1mmHg) gave **E12** as a viscous, slightly green oil (1.25g, 70% based on loss of starting material).

bp. 165°C / 0.1mmHg; $[\alpha]_D^{20}$ = +45.7° (c 0.685, DCM); (Found: C, 50.9; H, 5.18; N, 6.57. $C_{18}H_{22}N_2Br_2$ requires: C, 50.73; H, 5.2; N, 6.57%); $\nu_{max}$ (neat)/$cm^{-1}$ 3400, 3058.8, 2963.0, 1466.8, 1437.9; $\delta_H$ 1.31(6H, d, J = 6.6Hz, $C_1$-Me), 1.64(2H, s, NH), 2.54(4H, s, $C_2$-$CH_2$), 4.17(2H, q, J = 6.6Hz, $C_1$-CH), 7.08(2H, dt, J = 1.8, 7.3Hz, Ph-H), 7.31(2H, t, J = 6.2Hz, Ph-H), 7.49(4H, m, Ph-H); $\delta_C$ 22.71, 22.86, 47.27, 56.53, 123.74, 127.41, 127.50, 127.71, 127.80, 127.96, 128.11, 132.70, 132.86, 133.17, 144.51; m/z 186(98%), 184(100), 159(13), 157(14), 104(15), 77(35), 44(34), 28(20)

## E13 - (R,R)-N,N'-bis((α)-methyl,2-bromobenzyl)-1,3,2-diazaphosphole borane complex (23):

(R)-2-bromo-(α)-methylbenzylamine ethyl dimer (4.30g, 10.09mmol, 1eq.) was dissolved in dry THF (45ml) and $Et_3N$ (2.55g, 25.22mmol, 2.2eq.) was added. The resultant solution was cooled in an ice-bath and dichlorophenylphosphine (2.17g, 12.11mmol, 1.1eq.) was added slowly dropwise. Stirring was continued for two hours at RT and then the product was cooled in an ice-bath and borane-dimethyl sulphide complex (1.15g, 15.13mmol, 1.5eq.) was added dropwise. The resultant suspension was stirred at RT for one hour, poured very carefully into saturated $NaHCO_3$, extracted with DCM (4 x 100ml), dried over $Na_2SO_4$, filtered and concentrated under reduced pressure. Flash chromatography (10% EtOAc in petrol) gave a white amorphous solid. The amorphous solid produced was recrystallised from hexane to give **E13** as a white crystalline solid (3.84g, 69%).

mp. 126-127°C (hexane); $[\alpha]_D^{20}$ = -89.4° (c 1.46, $Et_2O$); (Found: C, 52.6; H, 5.20; N, 5.13. $C_{24}H_{28}N_2PBr_2B$ requires: C, 52.79; H, 5.17; N, 5.13%); $\nu_{max}$ (nujol)/$cm^{-1}$ 2333.1, 1565.2, 1465.7, 1372.4; $\delta_H$ 0.2-2.0(3H, br m, $BH_3$), 1.30(3H, d, J = 6.7Hz, $C_1$-Me), 1.38(3H, d, J = 6.9Hz, $C_1$-Me), 3.0-3.4(4H, m, $C_2$-$CH_2$), 4.77(2H, m, $C_1$-CH), 7.0(2H, m, Ph-H), 7.2-7.5(8H, m, Ph-H), 7.6(1H, m, Ph-H), 7.7-7.9(2H, m, Ph-H); $\delta_C$ 20.47, 20.81, 46.56, 47.35, 55.07, 55.79, 55.92, 122.99, 123.61, 127.52, 128.10, 128.25, 128.44, 128.48, 128.59, 131.56, 131.59, 131.69, 131.86, 132.74, 132.94, 142.23, 142.34, 142.41, 142.49; $\delta_P$ 100.25(d, J = 97.7Hz); m/z 101(22%0, 86(100), 58(40), 43(28), 30(48)

## E14 - 1,2-ethane-di(benzazaphosphole borane complex) (21):

(R,R)-N,N'-bis((α)-methyl,2-bromobenzyl)-1,3,2-diazaphosphole borane complex (2.0g, 3.66mmol, 1eq.) was dissolved in dry $Et_2O$ (40ml) and cooled to -70°C. *Tert*-butyllithium (9.89ml, 14.83mmol, 1.5M, 4.05eq.) was added dropwise. After 15 minutes at -70°C, phenyl phosphine dichloride (0.98g, 5.49mmol, 1.5eq.) was added

dropwise to the yellow solution. The resulting thick yellow suspension was stirred at -70°C for one hour and at RT for one hour. Borane-dimethyl sulphide complex (0.56g, 7.32mmol, 2.0eq.) was added dropwise and the resulting suspension was stirred vigorously at RT for one hour. The thick cream suspension was then poured slowly into saturated $NaHCO_3$ solution, extracted with DCM (3 x 100ml), dried over $Na_2SO_4$ and concentrated under reduced pressure to give an orange gum. Flash chromatography (gradient elution: 40-70% DCM / hexane) gave two fractions, both of which were white solids (1.19g, 64% and 0.25g, 14%). The first of these was an inseparable mixture of the *meso-* and *cis,cis-***21**, which was identified only by NMR, and the second of these was *trans-trans-***21**.

Data for (*trans,trans*)-**21**:

mp. 238-240°C (DCM); $[\alpha]_D^{20}$ = -259.6° (c 0.265, DCM); $\nu_{max}$ (nujol)/$cm^{-1}$ 2900, 2250, 1480, 1400; $\delta_H$ 0.2-1.8(6H, br m, $BH_3$), 1.48(6H, d, J = 6.4Hz, $C_1$-Me), 2.9(2H, m, $C_2$-$CH_2$), 3.2(2H, m, $C_2$-$CH_2$), 4.63(2H, q, J = 6.4Hz, $C_1$-CH), 7.2-7.6(18H, m, Ph-H); $\delta_C$ 21.07, 41.86/41.92, 62.05, 123.24, 123.32, 127.72, 128.44, 128.55, 128.64, 129.08, 129.19, 129.64, 130.38, 131.38, 131.75, 131.84, 133.85, 134.23, 148.28, 148.35; $\delta_P$ 75.7(d, J = 80.6Hz); m/z 503(11%), 493(24), 391(12), 281(22), 254(16), 240(36), 165(36), 149(100), 123(54), 109(97); Acc. Mass found 508.253987. $C_{30}H_{36}B_2N_2P_2$ requires 508.255028

Data for (*cis,cis*)-**21** and (*meso*)-**21**:

$\delta_H$ 0.2-1.8(6H, br m, $BH_3$), 1.50(3H, d, J = 6.4Hz, $C_1$-Me), 1.55(3H, d, J = 6.4Hz, $C_1$-Me), 3.0-3.6(4H, br m, $C_2$-$CH_2$), 4.42(0.66H, p, J = 7.0Hz, $C_1$-CH), 4.75(0.66H, p, J = 6.4Hz, $C_1$-CH), 4.94(0.66H, q, J = 6.2Hz, $C_1$-CH), 7.2-7.8(18H, m, Ph-H)

## E15 - N,N'-bis(2-bromobenzyl)-1,3,2-diazaphosphole borane complex:

1,2-(2-bromobenzyl)-ethylenediamine (1.00g, 2.51mmol, 1eq.) was dissolved in dry THF (10ml) and cooled in an ice-bath. $Et_3N$ (0.64g, 6.28mmol, 2.5eq.) was added followed by dichlorophenyl phosphine (0.54g, 3.01mmol, 1.2eq.) dropwise. The resulting suspension was stirred at RT for 2 hours and borane-dimethyl sulphide complex (0.29g, 3.77mmol, 1.5eq.) was added. After a further hour the mixture was poured carefully into saturated $NaHCO_3$, extracted with DCM (3 x 100ml), dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. Flash chromatography (15% EtOAc in petrol) gave a colourless oil which was crystallised from hexane to give **E15** as white crystals (0.65g, 50%).

mp. 101-102°C (hexane); (Found: C, 51.3; H, 4.78; N, 5.42. $C_{22}H_{24}N_2PBr_2B$ requires: C, 51.00; H, 4.67; N, 5.41%); $\nu_{max}$ (nujol)/$cm^{-1}$ 2921.5, 2376.7, 1462.1, 1436.0; $\delta_H$ 0.2-1.8(3H, br m, $BH_3$), 3.22(4H, m, $C_2$-$CH_2$), 4.14(4H, m, $C_1$-$CH_2$), 7.08(2H, dt, J = 1.7, 7.6Hz, Ph-H), 7.25(2H, dt, J = 1.1, 7.5Hz, Ph-H), 7.38-7.55(5H, m, Ph-H), 7.77(2H, dt, J = 1.6, 8.9Hz, Ph-H); $\delta_C$ 48.28, 50.24, 50.33, 123.88, 126.90, 127.54, 128.31, 128.40, 128.9, 131.56, 131.69, 131.86, 132.70, 134.00, 134.40, 136.74, 136.83; $\delta_P$ 105.5(d, J = 89.1Hz); m/z 518(1%), 517(2), 516(1), 425(100), 423(95), 171(35), 169(38)

## E16 - N,N'-(diphenylphosphino-borane complex)-1,2-((α)-methylbenzyl)-ethylenediamine (28):

1,2-((α)-methylbenzyl)-ethylenediamine[44] (3.0g, 11.18mmol, 1eq.) was dissolved in dry THF (40ml) and triethylamine (4.52g, 44.71mmol, 4.0eq.) was added. The resultant solution was cooled to 0°C and chlorodiphenyl phosphine (5.43g, 24.59mmol, 2.2eq.) was added dropwise. After stirring at RT for 2.5 hours borane-dimethyl sulphide complex (3.57g, 46.95mmol, 4.2eq.) was added. The resultant solution was stirred at RT for an hour, poured carefully into saturated $NaHCO_3$,

extracted with DCM (3 x 50ml), dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. The resultant viscous oil was crystallised from DCM / hexane to give **E16** as a white powder (4.81g, 65%).

mp. 160-162°C (DCM / hexane); $[\alpha]_D^{20}$ = +19.7° (c 1.065, DCM); $\nu_{max}$ (nujol)/$cm^{-1}$ 2924.3, 2853.6, 2724.4, 2378.6, 1463.4, 1377.0; $\delta_H$ 0-1.8(6H, br m, $BH_3$), 1.00(6H, d, J = 7.1Hz, $C_1$-Me), 2.49(4H, m, $C_2$-$CH_2$), 4.96(2H, sex, J = 6.8Hz, $C_1$-CH), 6.8-7.8(30H, m, Ph-H); $\delta_C$ 17.65, 17.83, 17.98, 46.03, 55.39, 55.54, 126.96, 127.41, 127.94, 128.38, 128.42, 128.49, 130.49, 130.94, 131.02, 131.13, 131.18, 131.53, 132.19, 132.30, 132.39, 132.48, 142.37, 142.43; $\delta_P$ 71.87; m/z 451(17%0, 374(30), 318(18), 398(12), 397(60), 201(12), 185(17), 149(12), 105(100); Acc. Mass (M-1)- Found 663.340062. $C_{42}H_{48}B_2N_2P_2$ requires 663.341211

## Morpholine deboration procedure:

Ligand was dissolved in dry morpholine (1ml) and heated to 70°C for two hours. Excess morpholine was removed by oil pump (0.1mmHg) while the vessel remained in the 70°C heating bath. After 10 minutes the vessel was cooled in an ice-bath and filled with dry Ar.

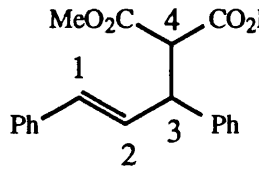
## DABCO deboration procedure:

Ligand and 1eq. of DABCO per borane molecule on the ligand were dissolved in dry toluene (1ml) and heated to 40°C for two hours. The solvent was removed by oil pump (0.1mmHg) while the vessel remained in the 40°C heating bath. After 10 minutes the vessel was cooled in an ice-bath and filled with dry Ar.

## Pd catalysed allylation reaction[12c]:

A solution of diallyl palladium chloride dimer in dry DCM (1ml) was added to the vessel containing deborated ligand. The resultant yellow solution was refluxed for two

hours, allowed to reach RT and sequentially was added 1, 3-diphenylpropenyl acetate[38] (0.2g, 0.79mmol, 1eq.) dissolved in dry DCM (1ml), dimethyl malonate (0.12g, 0.87mmol, 1.1eq.), bis-[trimethylsilyl] acetamide (0.18g, 0.87mmol, 1.1eq.) and KOAc (1mg). The resulting suspension was stirred at RT overnight, diluted with $Et_2O$, washed with ice-cold, saturated $NH_4Cl$ solution (2 x 20ml), dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. If time allowed it was left under high vacuum (0.1mmHg) overnight to remove excess dimethyl malonate. Flash chromatography (gradient elution: 5-10% EtOAc in petrol) gave the addition product as a slightly yellow oil that solidified on standing. This material gave $^1H$ NMR data identical to that described in reference 12c.



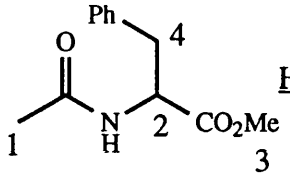

Allylic alkylation adduct

$\delta_H$ 3.50(3H, s, $CO_2Me$), 3.69(3H, s, $CO_2Me$), 3.96(1H, d, J = 11.0Hz, $C_4$-CH), 4.27(1H, dd, J = 8.4, 11.0Hz, $C_3$-CH), 6.33(1H, dd, J = 8.4, 15.8Hz, $C_2$-CH), 6.48(1H, d, J = 15.8Hz, $C_1$-CH), 7.15-7.4(10H, m, Ph-H)

## Hydrogenation reaction:

To the appropriate mol% of morpholine deborated ligand was added a dry, degassed DCM (1ml) solution of $[(COD)RhCl]_2$. The resulting orange solution was refluxed for two hours during which time it darkened to give an extremely deep red solution. This solution was allowed to reach RT and it was added to a solution of substrate (0.1g) in dry, degassed methanol (10ml). The resulting solution was degassed with several vacuum-hydrogen cycles and left under 1 atm of hydrogen for the appropriate length of time. Solvent was removed under reduced pressure and flash chromatography (70% EtOAc in petrol) gave **30** as a colourless oil. This material gave $^1H$ data identical to that

described in reference 68. Polarimetry was used to determine enantiomeric excess as described in reference 68.




Hydrogenation product, **30**

**30**: $\delta_H$ 1.98(3H, s, $C_1$-Me), 3.12(2H, m, $C_4$-$CH_2$), 3.73(3H, s, $C_3$-Me), 4.88(1H, m, $C_2$-CH), 6.00(1H, br d, J = 6.4Hz, NH), 7.15(2H, d, J = 6.7Hz, Ph-H), 7.25-7.30(3H, m, Ph-H); $[\alpha]_D^{20}$ = +9.9° (c 0.965, MeOH), 63%ee, S.

## Hydrosilylation reaction:

To the appropriate mol% of morpholine deborated ligand was added a dry, degassed DCM (1ml) solution of $[(COD)RhCl]_2$. The resulting orange solution was refluxed for two hours during which time it darkened to give an extremely deep red solution. This solution was cooled in an ice-bath and substrate (1mmol) and diphenylsilane (1.5mmol) were added sequentially. The resulting solution was stirred at the appropriate temperature for the necessary time and a solution of HCl in methanol (5ml, about 1.5M) was added slowly (Care; effervescence). The resulting solution was stirred at RT for 0.5hrs and concentrated under reduced pressure. Flash chromatography (gradient elution: 10-20% EtOAc in petrol) gave the reduction product as a colourless oil which was further purified by Kugel-Rohr distillation. Enantiomeric excess was determined using chiral HPLC and polarimetry.[62]

1-phenylethanol; $\delta_H$ 1.50(3H, d, J = 6.4Hz, $C_1$-Me), 1.84(1H, br s, OH), 4.90(1H, q, J = 6.4Hz, $C_1$-CH), 7.37(5H, m, Ph-H)

1-(2-chlorophenyl)ethanol; $\delta_H$ 1.47(3H, d, J = 6.4Hz, $C_1$-Me), 2.25(1H, br s, OH), 5.27(1H, q, J = 6.4Hz, $C_1$-CH), 7.18(1H, dt, J = 1.8, 11.3Hz, Ph-H), 7.25-

7.35(2H, m, Ph-H), 7.57(1H, dd, J = 1.7, 6.7Hz, Ph-H); $[\alpha]_D^{20}$ = -49.0° (c 0.255, chloroform), 78%ee, S.

1-(2-bromophenyl)ethanol; $\delta_H$ 1.47(3H, d, J = 6.4Hz, $C_1$-Me), 2.16(1H, br s, OH), 5.23(1H, q, J = 6.4Hz, $C_1$-CH), 7.12(1H, dt, J = 1.7, 7.7Hz, Ph-H), 7.34(1H, dt, J = 1.1, 7.5Hz, Ph-H), 7.51(1H, dd, J = 1.3, 8.0Hz, Ph-H), 7.58(1H, dd, J = 1.8, 7.8Hz, Ph-H); $[\alpha]_D^{19}$ = -36.9° (c 0.96, chloroform), 68%ee, S.

1-(2-iodophenyl)ethanol; $\delta_H$ 1.46(3H, d, J = 6.4Hz, $C_1$-Me), 2.03(1H, br s, OH), 5.07(1H, q, J = 6.4Hz, $C_1$-CH), 6.97(1H, dt, J = 1.8, 7.6Hz, Ph-H), 7.38(1H, t, J = 7.7Hz, Ph-H), 7.57(1H, dd, J = 1.7, 7.7Hz, Ph-H), 7.80(1H, d, J = 7.9Hz, Ph-H)

1-(1-naphthyl)ethanol; $\delta_H$ 1.62(3H, d, J = 6.4Hz, $C_1$-Me), 2.19(1H, br s, OH), 5.60(1H, q, J = 6.4Hz, $C_1$-CH), 7.4-7.54(3H, m, Ph-H), 7.63(1H, d, J = 7.1Hz, Ph-H), 7.74(1H, d, J = 8.3Hz, Ph-H), 7.8-7.9(1H, m, Ph-H), 8.02-8.12(1H, m, Ph-H)

## Heck reaction:

To the appropriate mol% of morpholine deborated ligand was added a dry, degassed DCM (1ml) solution of $[(C_3H_5)PdCl]_2$. The resulting yellow solution was refluxed for two hours during which time it darkened to give a deep orange solution. Careful concentration under reduced pressure using a vacuum line gave an orange gum. Norbornene (1.3mmol) was added and this was dissolved in dry DMSO (1ml). Sequentially was added phenyl triflate (1mmol), triethylamine (3.5mmol) and formic acid (3mmol). The solution was carefully degassed using four or five vacuum-argon cycles and stirred at 40°C overnight. The solution was allowed to reach RT, extracted with pentane (4 x 20ml), dried with $Na_2SO_4$, filtered and concentrated under reduced pressure. Filtration of a pentane solution of the resultant oil through a silica plug and concentration under reduced pressure gave the alkylation product as a colourless oil.

$\delta_H$ 1.1-1.4(3H, m, alkyl-H), 1.5-1.8(5H, m, alkyl-H), 2.35(2H, br s, alkyl-H), 2.74(1H, t, J = 8.6Hz, alkyl-H), 7.1-7.4(5H, m, Ph-H)[70]; $[\alpha]_D^{18}$ = +33.3° (c 0.475, chloroform), 80%ee.[23]

## NMR enantiomeric excess determination:

A sample of the allylation adduct (5-10mg) was weighed accurately into a screw-top vial. 0.4-0.45 eq. of Eu(HFC)3 was weighed out avoiding undue exposure to atmospheric moisture into another screw-top vial. The original allylation sample was dissolved in 0.6ml of dry CDCl3 and transferred into the vial containing the shift-reagent. After approximately 30 seconds of vigorous shaking the shift-reagent dissolved and the homogeneous yellow solution was transferred into an NMR tube. The $^1H$ spectrum of the sample shows a doublet and two singlets at approximately 4ppm (depending on the amount of shift-reagent used). The singlets are the signal given by each antipode for one of the methyl groups in the product. The doublet is the unresolved signal for the other methyl group in the product. The integral of the doublet and the sum of the integrals of the two singlets should thus give an approximately similar numerical value. The relative integrals of the two singlets can be used to give the enantiomeric excess of the sample analysed.

Using the (+)-antipode of the shift reagent, the singlet with highest ppm value corresponds to the (R)-enantiomer.

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6. For example, Pd is not very oxophilic but binds nitrogen based ligands whereas Cu binds strongly to sulphur based ligands.

7. This has been attributed to the strong π-acceptor properties of the P(III) atom giving synergistic back-bonding, increasing binding strength and hence increasing the mole-percentage of bound, and thus active ligand.

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48. The heterocycle is only sparingly soluble in ether at -70°C. The only effect that this has is that the larger the scale of the reaction, the longer it has to be left at -70°C before electrophile is added.

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# Appendix - X-ray Data

## 1. (R)-*trans*-**15**:

A crystal of approximate dimensions 0.4 x 0.2 x 0.2 mm was used for data collection. *Crystal data*: $C_{20}H_{31}N_2B_2P$, $M$ = 352.1 orthorhombic, $a$ = 9.604(1), $b$ = 10.496(2), $c$ = 21.259(3)Å, $U$ = 2143.0 Å$^3$, space group $P2_12_12_1$, $Z$ = 4, $D_c$ = 1.09 gcm$^{-3}$, $\mu$(Mo-$K_\alpha$) = 1.30 cm$^{-1}$, $F$(000) = 760. Data were measured at room temperature on a CAD4 automatic four-circle diffractometer in the range $2 \leq \theta \leq 24°$. 1946 reflections were collected of which 1115 were unique with $I \geq 2\sigma(I)$. Data were corrected for Lorentz and polarization but not for absorption. The structure was solved by Direct methods and refined using the SHELX[72,73] suite of programs. In the final least squares cycles all atoms were allowed to vibrate anisotropically. Hydrogen atoms were included at calculated positions except in the instance of the $BH_3$ functionalities, where the protons (H1, H2, H3, H4, H5, H6) were located in an advanced Difference Fourier and positionally refined. Final residuals after 10 cycles of least squares were $R$ = 0.0432, $R_w$ = 0.0345, for a weighting scheme of w = 2.5889/[$\sigma^2$(F) + 0.000106(F)$^2$]. Max. final shift/esd was 0.000. The max. and min. residual densities were 0.06 and -0.07 eÅ$^{-3}$ respectively.

TABLE 1

Fractional atomic co-ordinates ($x10^4$) and equivalent isotropic temperature factors ($Å^2 x10^3$) for *Trans*-**15**

| | x | y | z | U |
|---|---|---|---|---|
| P(1) | 1204(2) | 8241(1) | 6222(1) | 52 |
| B(1) | -649(8) | 8533(8) | 6467(4) | 76(3) |
| B(2) | 1619(11) | 12085(7) | 4744(4) | 84(3) |
| N(1) | 1567(5) | 8183(4) | 5455(2) | 58(2) |
| N(2) | 2529(4) | 10976(4) | 4397(2) | 51(2) |
| C(1) | 1825(5) | 6646(5) | 6342(2) | 48(2) |
| C(2) | 1814(6) | 5940(6) | 6893(2) | 62(2) |
| C(3) | 2311(7) | 4701(6) | 6866(3) | 74(3) |
| C(4) | 2787(6) | 4197(5) | 6314(3) | 71(3) |
| C(5) | 2789(6) | 4890(5) | 5761(3) | 59(3) |
| C(6) | 2293(5) | 6142(5) | 5780(2) | 48(2) |
| C(7) | 2200(5) | 7016(5) | 5216(2) | 49(2) |
| C(8) | 1355(6) | 6440(5) | 4675(2) | 67(2) |
| C(9) | 1319(6) | 9287(5) | 5046(2) | 61(2) |
| C(10) | 2681(5) | 9840(5) | 4818(2) | 56(2) |
| C(11) | 1909(6) | 10630(5) | 3781(2) | 64(2) |
| C(12) | 2343(8) | 11701(6) | 3355(3) | 96(3) |
| C(13) | 3737(8) | 12134(6) | 3593(3) | 102(3) |
| C(14) | 3933(6) | 11430(5) | 4213(3) | 83(3) |
| C(15) | 2406(7) | 9301(6) | 6614(2) | 54(2) |
| C(16) | 1968(8) | 10325(6) | 6959(3) | 75(2) |
| C(17) | 2892(11) | 11117(6) | 7258(3) | 92(4) |
| C(18) | 4272(12) | 10892(9) | 7215(4) | 110(4) |

| | | | | |
|---|---|---|---|---|
| C(19) | 4754(8) | 9882(9) | 6862(3) | 111(4) |
| C(20) | 3816(8) | 9101(6) | 6570(2) | 80(3) |

TABLE 2

Fractional atomic co-ordinates ($x10^4$) for *Trans*-**15**

| | x | y | z |
|---|---|---|---|
| P(1) | 1204(2) | 8241(1) | 6222(1) |
| B(1) | -649(8) | 8533(8) | 6467(4) |
| B(2) | 1619(11) | 12085(7) | 4744(4) |
| N(1) | 1567(5) | 8183(4) | 5455(2) |
| N(2) | 2529(4) | 10976(4) | 4397(2) |
| C(1) | 1825(5) | 6646(5) | 6342(2) |
| C(2) | 1814(6) | 5940(6) | 6893(2) |
| C(3) | 2311(7) | 4701(6) | 6866(3) |
| C(4) | 2787(6) | 4197(5) | 6314(3) |
| C(5) | 2789(6) | 4890(5) | 5761(3) |
| C(6) | 2293(5) | 6142(5) | 5780(2) |
| C(7) | 2200(5) | 7016(5) | 5216(2) |
| C(8) | 1355(6) | 6440(5) | 4675(2) |
| C(9) | 1319(6) | 9287(5) | 5046(2) |
| C(10) | 2681(5) | 9840(5) | 4818(2) |
| C(11) | 1909(6) | 10630(5) | 3781(2) |
| C(12) | 2343(8) | 11701(6) | 3355(3) |
| C(13) | 3737(8) | 12134(6) | 3593(3) |
| C(14) | 3933(6) | 11430(5) | 4213(3) |
| C(15) | 2406(7) | 9301(6) | 6614(2) |

| | | | |
|---|---|---|---|
| C(16) | 1968(8) | 10325(6) | 6959(3) |
| C(17) | 2892(11) | 11117(6) | 7258(3) |
| C(18) | 4272(12) | 10892(9) | 7215(4) |
| C(19) | 4754(8) | 9882(9) | 6862(3) |
| C(20) | 3816(8) | 9101(6) | 6570(2) |

TABLE 3

Anisotropic temperature factors (Å x$10^3$) for *Trans*-**15**

| | $U_{11}$ | $U_{22}$ | $U_{33}$ | $U_{23}$ | $U_{13}$ | $U_{12}$ |
|---|---|---|---|---|---|---|
| P(1) | 55(1) | 58(1) | 43(1) | 0(1) | 7(1) | 3(1) |
| B(1) | 67(5) | 88(6) | 74(5) | -2(5) | 3(4) | 2(5) |
| B(2) | 104(7) | 58(5) | 89(6) | -10(4) | 23(5) | 7(5) |
| N(1) | 80(3) | 53(3) | 41(2) | 6(3) | 7(2) | 13(3) |
| N(2) | 54(3) | 46(3) | 52(3) | -2(2) | -4(2) | -3(3) |
| C(1) | 51(3) | 52(3) | 40(3) | 1(3) | -1(2) | -5(3) |
| C(2) | 67(4) | 68(4) | 51(4) | 7(3) | 0(3) | -8(4) |
| C(3) | 86(5) | 61(4) | 73(5) | 15(3) | -4(4) | -10(4) |
| C(4) | 69(4) | 54(4) | 89(4) | 7(4) | -4(4) | 3(4) |
| C(5) | 51(4) | 60(4) | 66(4) | -2(3) | 12(3) | 0(3) |
| C(6) | 36(3) | 54(3) | 53(3) | 4(3) | -1(3) | -6(3) |
| C(7) | 40(3) | 63(4) | 44(3) | 1(3) | 10(3) | -4(3) |
| C(8) | 64(4) | 82(4) | 56(3) | -2(3) | -1(4) | -13(4) |
| C(9) | 54(4) | 73(4) | 56(3) | 10(3) | 0(3) | 7(4) |
| C(10) | 50(4) | 62(4) | 57(3) | 2(3) | -5(3) | 9(3) |
| C(11) | 79(4) | 64(3) | 49(3) | 3(3) | -5(4) | -7(3) |
| C(12) | 127(6) | 84(5) | 78(4) | 23(4) | -1(5) | -4(6) |

| | | | | | | |
|---|---|---|---|---|---|---|
| C(13) | 101(6) | 79(5) | 126(6) | 28(4) | 42(5) | -6(5) |
| C(14) | 58(4) | 82(5) | 108(5) | 12(4) | 3(4) | -15(4) |
| C(15) | 57(4) | 59(4) | 46(3) | 13(3) | 0(3) | -7(4) |
| C(16) | 91(5) | 50(4) | 85(5) | 0(4) | -12(4) | 10(4) |
| C(17) | 148(8) | 44(4) | 85(5) | -4(4) | -19(6) | -9(6) |
| C(18) | 132(9) | 113(7) | 85(6) | 13(6) | -20(6) | -73(7) |
| C(19) | 77(6) | 173(9) | 82(5) | -18(6) | 11(5) | -39(7) |
| C(20) | 76(5) | 105(5) | 60(4) | -24(4) | 4(4) | -23(5) |

The temperature factor exponent takes the form:

$-2\ (U\ .h\ .a^* + \ldots + 2U\ .h.k.a^*.b^*)$

TABLE 4

Hydrogen fractional atomic co-ordinates ($x10^4$) and isotropic temperature factors ($Å^2$ $x10^3$) for *Trans*-**15**

| | x | y | z | U |
|---|---|---|---|---|
| H(21) | 1473(6) | 6296(6) | 7280(2) | 89(4) |
| H(31) | 2321(7) | 4190(6) | 7241(3) | 89(4) |
| H(41) | 3129(6) | 3338(5) | 6310(3) | 89(4) |
| H(51) | 3121(6) | 4523(5) | 5375(3) | 89(4) |
| H(71) | 3102(5) | 7167(5) | 5036(2) | 89(4) |
| H(81) | 1802(6) | 5676(5) | 4531(2) | 89(4) |
| H(82) | 1298(6) | 7041(5) | 4336(2) | 89(4) |
| H(83) | 434(6) | 6240(5) | 4821(2) | 89(4) |
| H(91) | 777(6) | 9022(5) | 4690(2) | 89(4) |
| H(92) | 817(6) | 9925(5) | 5277(2) | 89(4) |
| H(101) | 3173(5) | 9190(5) | 4591(2) | 89(4) |

| | | | | |
|---|---|---|---|---|
| H(102) | 3215(5) | 10091(5) | 5179(2) | 89(4) |
| H(111) | 2270(6) | 9830(5) | 3635(2) | 89(4) |
| H(112) | 913(6) | 10580(5) | 3811(2) | 89(4) |
| H(121) | 1681(8) | 12385(6) | 3374(3) | 89(4) |
| H(122) | 2419(8) | 11404(6) | 2929(3) | 89(4) |
| H(131) | 4460(8) | 11911(6) | 3300(3) | 89(4) |
| H(131) | 3740(8) | 13038(6) | 3659(3) | 89(4) |
| H(141) | 4300(6) | 11994(5) | 4527(3) | 89(4) |
| H(142) | 4553(6) | 10721(5) | 4159(3) | 89(4) |
| H(161) | 989(8) | 10494(6) | 6993(3) | 89(4) |
| H(171) | 2557(11) | 11830(6) | 7497(3) | 89(4) |
| H(181) | 4919(12) | 11435(9) | 7430(4) | 89(4) |
| H(191) | 5735(8) | 9730(9) | 6823(3) | 89(4) |
| H(201) | 4152(8) | 8393(6) | 6327(2) | 89(4) |
| H(5) | 2032(53) | 12986(50) | 4535(22) | 89(4) |
| H(3) | -1238(59) | 7777(44) | 6315(24) | 89(4) |
| H(2) | -937(56) | 9396(45) | 6318(25) | 89(4) |
| H(4) | 447(56) | 11817(49) | 4744(22) | 89(4) |
| H(1) | -632(51) | 8326(49) | 6942(24) | 89(4) |
| H(6) | 2155(51) | 12100(45) | 5249(25) | 89(4) |

TABLE 5

Bond lengths (Å) for *Trans*-**15**

| | | | |
|---|---|---|---|
| B(1)-P(1) | 1.879(10) | N(1)-P(1) | 1.669(6) |
| C(1)-P(1) | 1.795(7) | C(15)-P(1) | 1.806(8) |
| N(2)-B(2) | 1.631(10) | C(7)-N(1) | 1.460(6) |

| | | | |
|---|---|---|---|
| C(9)-N(1) | 1.467(7) | C(10)-N(2) | 1.498(7) |
| C(11)-N(2) | 1.483(7) | C(14)-N(2) | 1.482(8) |
| C(2)-C(1) | 1.387(7) | C(6)-C(1) | 1.381(7) |
| C(3)-C(2) | 1.386(8) | C(4)-C(3) | 1.366(8) |
| C(5)-C(4) | 1.383(8) | C(6)-C(5) | 1.398(7) |
| C(7)-C(6) | 1.513(8) | C(8)-C(7) | 1.531(8) |
| C(10)-C(9) | 1.511(9) | C(12)-C(11) | 1.503(9) |
| C(13)-C(12) | 1.502(10) | C(14)-C(13) | 1.524(9) |
| C(16)-C(15) | 1.368(8) | C(20)-C(15) | 1.373(9) |
| C(17)-C(16) | 1.372(10) | C(18)-C(17) | 1.350(11) |
| C(19)-C(18) | 1.377(11) | C(20)-C(19) | 1.368(9) |
| H(3)-B(1) | 1.026(50) | H(2)-B(1) | 0.999(45) |
| H(1)-B(1) | 1.033(49) | H(5)-B(2) | 1.117(50) |
| H(4)-B(2) | 1.161(50) | H(6)-B(2) | 1.191(51) |
| H(21)-C(2) | 0.960 | H(31)-C(3) | 0.960 |
| H(41)-C(4) | 0.960 | H(51)-C(5) | 0.960 |
| H(71)-C(7) | 0.960 | H(81)-C(8) | 0.960 |
| H(82)-C(8) | 0.960 | H(83)-C(8) | 0.960 |
| H(91)-C(9) | 0.960 | H(92)-C(9) | 0.960 |
| H(101)-C(10) | 0.960 | H(102)-C(10) | 0.960 |
| H(111)-C(11) | 0.960 | H(112)-C(11) | 0.960 |
| H(121)-C(12) | 0.960 | H(122)-C(12) | 0.960 |
| H(131)-C(13) | 0.960 | H(131)-C(13) | 0.960 |
| H(141)-C(14) | 0.960 | H(142)-C(14) | 0.960 |
| H(161)-C(16) | 0.960 | H(171)-C(17) | 0.960 |
| H(181)-C(18) | 0.960 | H(191)-C(19) | 0.960 |

| | | | |
|---|---|---|---|
| H(201)-C(20) | 0.960 | | |

TABLE 6

Bond angles (°) for *Trans*-**15**

| | | | |
|---|---|---|---|
| N(1)-P(1)-B(1) | 118.3(4) | C(1)-P(1)-B(1) | 115.3(4) |
| C(1)-P(1)-N(1) | 92.0(3) | C(15)-P(1)-B(1) | 112.2(5) |
| C(15)-P(1)-N(1) | 109.8(3) | C(15)-P(1)-C(1) | 107.3(3) |
| C(7)-N(1)-P(1) | 117.3(4) | C(9)-N(1)-P(1) | 121.1(4) |
| C(9)-N(1)-C(7) | 121.5(5) | C(10)-N(2)-B(2) | 110.5(5) |
| C(11)-N(2)-B(2) | 111.0(6) | C(11)-N(2)-C(10) | 111.8(5) |
| C(14)-N(2)-B(2) | 112.1(6) | C(14)-N(2)-C(10) | 108.9(5) |
| C(14)-N(2)-C(11) | 102.2(5) | C(2)-C(1)-P(1) | 128.0(5) |
| C(6)-C(1)-P(1) | 110.1(5) | C(6)-C(1)-C(2) | 121.9(6) |
| C(3)-C(2)-C(1) | 117.6(6) | C(4)-C(3)-C(2) | 120.9(7) |
| C(5)-C(4)-C(3) | 121.8(6) | C(6)-C(5)-C(4) | 118.0(6) |
| C(5)-C(6)-C(1) | 119.7(6) | C(7)-C(6)-C(1) | 115.8(5) |
| C(7)-C(6)-C(5) | 124.5(6) | C(6)-C(7)-N(1) | 104.9(5) |
| C(8)-C(7)-N(1) | 111.8(5) | C(8)-C(7)-C(6) | 112.8(5) |
| C(10)-C(9)-N(1) | 110.7(5) | C(9)-C(10)-N(2) | 114.4(5) |
| C(12)-C(11)-N(2) | 103.8(5) | C(13)-C(12)-C(11) | 105.7(6) |
| C(14)-C(13)-C(12) | 104.8(6) | C(13)-C(14)-N(2) | 105.8(6) |
| C(16)-C(15)-P(1) | 122.3(7) | C(20)-C(15)-P(1) | 120.3(6) |
| C(20)-C(15)-C(16) | 117.4(7) | C(17)-C(16)-C(15) | 121.8(8) |
| C(18)-C(17)-C(16) | 119.8(9) | C(19)-C(18)-C(17) | 120.1(9) |
| C(20)-C(19)-C(18) | 119.2(8) | C(19)-C(20)-C(15) | 121.7(8) |
| H(3)-B(1)-P(1) | 108.0(31) | H(2)-B(1)-P(1) | 108.8(34) |

| | | | |
|---|---|---|---|
| H(2)-B(1)-H(3) | 116.7(45) | H(1)-B(1)-P(1) | 102.8(30) |
| H(1)-B(1)-H(3) | 98.8(43) | H(1)-B(1)-H(2) | 120.3(47) |
| H(5)-B(2)-N(2) | 103.5(27) | H(4)-B(2)-N(2) | 110.3(28) |
| H(4)-B(2)-H(5) | 123.3(40) | H(6)-B(2)-N(2) | 100.7(26) |
| H(6)-B(2)-H(5) | 101.2(37) | H(6)-B(2)-H(4) | 115.0(37) |
| H(21)-C(2)-C(1) | 121.2(4) | C(3)-C(2)-H(21) | 121.2(5) |
| H(31)-C(3)-C(2) | 119.5(5) | C(4)-C(3)-H(31) | 119.5(5) |
| H(41)-C(4)-C(3) | 119.1(5) | C(5)-C(4)-H(41) | 119.1(5) |
| H(51)-C(5)-C(4) | 121.0(5) | C(6)-C(5)-H(51) | 121.0(4) |
| H(71)-C(7)-N(1) | 112.1(3) | H(71)-C(7)-C(6) | 111.3(4) |
| C(8)-C(7)-H(71) | 104.2(4) | H(81)-C(8)-C(7) | 109.4(4) |
| H(82)-C(8)-C(7) | 109.5(4) | H(82)-C(8)-H(81) | 109.5 |
| H(83)-C(8)-C(7) | 109.5(4) | H(83)-C(8)-H(81) | 109.5 |
| H(83)-C(8)-H(82) | 109.5 | H(91)-C(9)-N(1) | 109.1(4) |
| H(92)-C(9)-N(1) | 109.2(4) | H(92)-C(9)-H(91) | 109.5 |
| C(10)-C(9)-H(91) | 109.1(4) | C(10)-C(9)-H(92) | 109.2(4) |
| H(101)-C(10)-N(2) | 108.3(3) | H(101)-C(10)-C(9) | 108.3(4) |
| H(102)-C(10)-N(2) | 108.2(3) | H(102)-C(10)-C(9) | 108.2(4) |
| H(102)-C(10)-H(101) | 109.5 | H(111)-C(11)-N(2) | 110.9(4) |
| H(112)-C(11)-N(2) | 110.8(4) | H(112)-C(11)-H(111) | 109.5 |
| C(12)-C(11)-H(111) | 110.9(4) | C(12)-C(11)-H(112) | 110.8(5) |
| H(121)-C(12)-C(11) | 110.5(5) | H(122)-C(12)-C(11) | 110.3(4) |
| H(122)-C(12)-H(121) | 109.5 | C(13)-C(12)-H(121) | 110.5(5) |
| C(13)-C(12)-H(122) | 110.4(5) | H(131)-C(13)-C(12) | 110.7(5) |
| H(131)-C(13)-C(12) | 110.6(5) | H(131)-C(13)-H(131) | 109.5 |
| C(14)-C(13)-H(131) | 110.7(5) | C(14)-C(13)-H(131) | 110.6(4) |

| | | | |
|---|---|---|---|
| H(141)-C(14)-N(2) | 110.4(4) | H(141)-C(14)-C(13) | 110.4(4) |
| H(142)-C(14)-N(2) | 110.4(4) | H(142)-C(14)-C(13) | 110.3(4) |
| H(142)-C(14)-H(141) | 109.5 | H(161)-C(16)-C(15) | 119.1(5) |
| C(17)-C(16)-H(161) | 119.1(6) | H(171)-C(17)-C(16) | 120.1(6) |
| C(18)-C(17)-H(171) | 120.1(7) | H(181)-C(18)-C(17) | 119.9(7) |
| C(19)-C(18)-H(181) | 119.9(7) | H(191)-C(19)-C(18) | 120.4(7) |
| C(20)-C(19)-H(191) | 120.4(6) | H(201)-C(20)-C(15) | 119.1(5) |
| H(201)-C(20)-C(19) | 119.1(6) | | |

TABLE 7

Selected non-bonded distances (Å) for *Trans*-**15**

Intramolecular:

| | | | |
|---|---|---|---|
| C(2)-P(1) | 2.866 | H(21)-P(1) | 3.048 |
| C(6)-P(1) | 2.614 | C(7)-P(1) | 2.674 |
| H(71)-P(1) | 3.310 | C(8)-P(1) | 3.797 |
| C(9)-P(1) | 2.733 | H(92)-P(1) | 2.702 |
| C(10)-P(1) | 3.706 | C(16)-P(1) | 2.788 |
| H(161)-P(1) | 2.883 | C(20)-P(1) | 2.766 |
| H(201)-P(1) | 2.845 | H(3)-P(1) | 2.403 |
| H(2)-P(1) | 2.396 | H(1)-P(1) | 2.336 |
| N(1)-B(1) | 3.047 | C(1)-B(1) | 3.104 |
| C(15)-B(1) | 3.058 | C(16)-B(1) | 3.309 |
| H(161)-B(1) | 2.821 | C(9)-B(2) | 3.021 |
| H(92)-B(2) | 2.649 | C(10)-B(2) | 2.572 |
| H(102)-B(2) | 2.755 | C(11)-B(2) | 2.569 |
| H(112)-B(2) | 2.625 | C(12)-B(2) | 3.061 |
| H(121)-B(2) | 2.929 | C(13)-B(2) | 3.183 |

| | | | |
|---|---|---|---|
| C(14)-B(2) | 2.585 | H(141)-B(2) | 2.617 |
| C(1)-N(1) | 2.493 | C(6)-N(1) | 2.357 |
| H(71)-N(1) | 2.027 | C(8)-N(1) | 2.478 |
| H(82)-N(1) | 2.677 | H(83)-N(1) | 2.676 |
| H(91)-N(1) | 2.000 | H(92)-N(1) | 2.001 |
| C(10)-N(1) | 2.450 | H(101)-N(1) | 2.621 |
| H(102)-N(1) | 2.619 | C(15)-N(1) | 2.844 |
| C(20)-N(1) | 3.347 | C(9)-N(2) | 2.529 |
| H(91)-N(2) | 2.724 | H(92)-N(2) | 2.723 |
| H(101)-N(2) | 2.017 | H(102)-N(2) | 2.016 |
| H(111)-N(2) | 2.034 | H(112)-N(2) | 2.033 |
| C(12)-N(2) | 2.350 | H(121)-N(2) | 2.753 |
| C(13)-N(2) | 2.398 | H(131)-N(2) | 2.916 |
| H(141)-N(2) | 2.028 | H(142)-N(2) | 2.027 |
| H(5)-N(2) | 2.183 | H(4)-N(2) | 2.306 |
| H(6)-N(2) | 2.191 | H(21)-C(1) | 2.056 |
| C(3)-C(1) | 2.373 | C(4)-C(1) | 2.732 |
| C(5)-C(1) | 2.404 | C(7)-C(1) | 2.452 |
| C(15)-C(1) | 2.900 | C(20)-C(1) | 3.245 |
| H(201)-C(1) | 2.891 | H(31)-C(2) | 2.038 |
| C(4)-C(2) | 2.395 | C(5)-C(2) | 2.808 |
| C(6)-C(2) | 2.420 | C(3)-H(21) | 2.055 |
| H(31)-H(21) | 2.357 | H(41)-C(3) | 2.016 |
| C(5)-C(3) | 2.402 | C(6)-C(3) | 2.761 |
| C(4)-H(31) | 2.021 | H(41)-H(31) | 2.307 |
| H(51)-C(4) | 2.050 | C(6)-C(4) | 2.384 |

| | | | |
|---|---|---|---|
| C(5)-H(41) | 2.031 | H(51)-H(41) | 2.344 |
| C(7)-C(5) | 2.577 | H(71)-C(5) | 2.860 |
| C(8)-C(5) | 3.141 | H(81)-C(5) | 2.902 |
| C(6)-H(51) | 2.064 | C(7)-H(51) | 2.782 |
| C(8)-H(51) | 3.023 | H(81)-H(51) | 2.508 |
| H(71)-C(6) | 2.065 | C(8)-C(6) | 2.535 |
| H(81)-C(6) | 2.742 | H(83)-C(6) | 2.713 |
| H(81)-C(7) | 2.060 | H(82)-C(7) | 2.061 |
| H(83)-C(7) | 2.061 | C(9)-C(7) | 2.555 |
| H(91)-C(7) | 2.748 | C(10)-C(7) | 3.117 |
| H(101)-C(7) | 2.800 | C(8)-H(71) | 1.997 |
| H(81)-H(71) | 2.272 | H(82)-H(71) | 2.288 |
| C(9)-H(71) | 2.807 | C(10)-H(71) | 2.872 |
| H(101)-H(71) | 2.325 | C(9)-C(8) | 3.090 |
| H(91)-C(8) | 2.767 | H(82)-H(81) | 1.568 |
| H(83)-H(81) | 1.568 | H(83)-H(82) | 1.568 |
| C(9)-H(82) | 2.799 | H(91)-H(82) | 2.267 |
| H(101)-C(9) | 2.029 | H(102)-C(9) | 2.027 |
| C(11)-C(9) | 3.088 | H(112)-C(9) | 2.982 |
| C(15)-C(9) | 3.492 | H(4)-C(9) | 2.858 |
| H(92)-H(91) | 1.568 | C(10)-H(91) | 2.038 |
| H(101)-H(91) | 2.317 | C(11)-H(91) | 2.785 |
| H(112)-H(91) | 2.486 | C(10)-H(92) | 2.040 |
| H(102)-H(92) | 2.319 | H(4)-H(92) | 2.314 |
| H(6)-H(92) | 2.621 | C(11)-C(10) | 2.469 |
| H(111)-C(10) | 2.547 | H(112)-C(10) | 2.841 |

| | | | |
|---|---|---|---|
| C(14)-C(10) | 2.426 | H(141)-C(10) | 2.812 |
| H(142)-C(10) | 2.461 | H(4)-C(10) | 2.989 |
| H(6)-C(10) | 2.592 | H(102)-H(101) | 1.568 |
| C(11)-H(101) | 2.593 | H(111)-H(101) | 2.312 |
| C(14)-H(101) | 2.589 | H(142)-H(101) | 2.277 |
| C(14)-H(102) | 2.583 | H(141)-H(102) | 2.645 |
| H(142)-H(102) | 2.608 | H(6)-H(102) | 2.347 |
| H(121)-C(11) | 2.047 | H(122)-C(11) | 2.046 |
| C(13)-C(11) | 2.395 | H(131)-C(11) | 2.976 |
| C(14)-C(11) | 2.307 | H(142)-C(11) | 2.665 |
| H(5)-C(11) | 2.949 | H(4)-C(11) | 2.777 |
| H(112)-H(111) | 1.568 | C(12)-H(111) | 2.053 |
| H(122)-H(111) | 2.236 | C(13)-H(111) | 2.800 |
| C(14)-H(111) | 2.624 | H(142)-H(111) | 2.632 |
| C(12)-H(112) | 2.052 | H(121)-H(112) | 2.235 |
| H(122)-H(112) | 2.521 | H(4)-H(112) | 2.412 |
| H(131)-C(12) | 2.048 | H(131)-C(12) | 2.047 |
| C(14)-C(12) | 2.396 | H(142)-C(12) | 2.913 |
| H(5)-C(12) | 2.864 | H(122)-H(121) | 1.568 |
| C(13)-H(121) | 2.045 | H(131)-H(121) | 2.179 |
| C(14)-H(121) | 2.977 | H(5)-H(121) | 2.569 |
| C(13)-H(122) | 2.044 | H(131)-H(122) | 2.179 |
| H(131)-H(122) | 2.639 | H(141)-C(13) | 2.065 |
| H(142)-C(13) | 2.064 | H(5)-C(13) | 2.737 |
| H(131)-H(131) | 1.568 | C(14)-H(131) | 2.068 |
| H(141)-H(131) | 2.614 | H(142)-H(131) | 2.213 |

| | | | |
|---|---|---|---|
| C(14)-H(131) | 2.067 | H(141)-H(131) | 2.214 |
| H(5)-H(131) | 2.482 | H(5)-C(14) | 2.543 |
| H(6)-C(14) | 2.873 | H(142)-H(141) | 1.568 |
| H(5)-H(141) | 2.414 | H(6)-H(141) | 2.570 |
| H(161)-C(15) | 2.017 | C(17)-C(15) | 2.393 |
| C(18)-C(15) | 2.763 | C(19)-C(15) | 2.395 |
| H(201)-C(15) | 2.023 | H(171)-C(16) | 2.031 |
| C(18)-C(16) | 2.355 | C(19)-C(16) | 2.723 |
| C(20)-C(16) | 2.342 | C(17)-H(161) | 2.021 |
| H(171)-H(161) | 2.321 | H(2)-H(161) | 2.609 |
| H(181)-C(17) | 2.009 | C(19)-C(17) | 2.363 |
| C(20)-C(17) | 2.722 | C(18)-H(171) | 2.011 |
| H(181)-H(171) | 2.310 | H(191)-C(18) | 2.039 |
| C(20)-C(18) | 2.368 | C(19)-H(181) | 2.034 |
| H(191)-H(181) | 2.342 | H(201)-C(19) | 2.018 |
| C(20)-H(191) | 2.031 | H(201)-H(191) | 2.322 |
| H(4)-H(5) | 2.005 | H(6)-H(5) | 1.784 |
| H(2)-H(3) | 1.724 | H(1)-H(3) | 1.563 |
| H(1)-H(2) | 1.762 | H(6)-H(4) | 1.984 |

Intermolecular:

| | | | |
|---|---|---|---|
| H(141)-B(2a) | 2.880 | H(171)-H(31b) | 2.547 |
| H(1)-H(31c) | 2.545 | H(112)-C(4d) | 3.024 |
| H(5)-H(51b) | 2.624 | H(4)-H(51d) | 2.652 |
| H(201)-C(8e) | 3.007 | H(201)-H(82e) | 2.538 |
| C(10)-H(83e) | 2.978 | H(101)-H(83e) | 2.546 |

| | | | |
|---|---|---|---|
| H(102)-H(83e) | 2.548 | C(15)-H(122f) | 2.898 |
| C(16)-H(122f) | 2.809 | C(17)-H(122f) | 3.021 |
| H(4)-H(141g) | 2.275 | | |

Key to symmetry operations relating designated atoms to reference atoms at (x,y,z):

(a) 0.5+x,2.5-y,1.0-z

(b) x,1.0+y,z

(c) -x,0.5+y,1.5-z

(d) -0.5+x,1.5-y,1.0-z

(e) 0.5+x,1.5-y,1.0-z

(f) 0.5-x,2.0-y,0.5+z

(g) -0.5+x,2.5-y,1.0-z

## 2. (R)-*trans*-**18**:

A crystal of approximate dimensions 0.3 x 0.3 x 0.2 mm was used for data collection. *Crystal data*: $C_{20}H_{35}NPBSi$, $M = 479.5$ monoclinic, $a = 9.016(2)$, $b = 14.218(2)$, $c = 11.413(2)$Å, $U = 1378.9$ Å$^3$, space group $P2_1$, $Z = 2$, $D_C = 1.16$ gcm$^{-3}$, $\mu$(Mo-K$\alpha$) = 1.60 cm$^{-1}$, $F(000) = 512$. Data were measured at room temperature on a CAD4 automatic four-circle diffractometer in the range $2 \leq \theta \leq 24°$. 2417 reflections were collected of which 1964 were unique with $I \geq 2\sigma(I)$. Data were corrected for Lorentz and polarization but not for absorption. The structure was solved by Direct methods and refined using the SHELX[72,73] suite of programs. In the final least squares cycles all atoms were allowed to vibrate anisotropically. Hydrogen atoms were included at calculated positions except in the instance of the $BH_3$ functionality, where the protons (H1, H2, H3) were located in an advanced Difference Fourier and refined at a distance of 1.04 Å from the parent boron atom. Final residuals after 10 cycles of least squares were $R = 0.0310$, $R_W = 0.0334$, for a weighting scheme of $w = 1.4815/[\sigma^2(F) + 0.001089(F)^2]$. Max. final shift/esd was 0.000. The max. and min. residual densities were 0.07 and -0.05 eÅ$^{-3}$ respectively.

TABLE 1

Fractional atomic co-ordinates ($x10^4$) and equivalent isotropic temperature factors ($Å^2 x10^3$) for *Trans*-**18**

| | x | y | z | U |
|---|---|---|---|---|
| Si(1) | 5005(1) | 2493 | 8270(1) | 41 |
| P(1) | 3280(1) | 1093(1) | 6210(1) | 37 |
| B(1) | 2609(6) | 28(3) | 6947(5) | 54(2) |
| N(1) | 3477(3) | 2163(2) | 6889(2) | 39(1) |
| C(1) | 1771(4) | 1473(3) | 4823(3) | 45(1) |
| C(2) | 1030(4) | 952(4) | 3740(3) | 64(2) |
| C(3) | -112(5) | 1379(5) | 2792(4) | 82(2) |
| C(4) | -532(5) | 2300(5) | 2895(4) | 84(2) |
| C(5) | 177(4) | 2810(3) | 3967(4) | 67(2) |
| C(6) | 1357(4) | 2388(3) | 4943(3) | 47(1) |
| C(7) | 2211(4) | 2833(3) | 6180(4) | 49(1) |
| C(8) | 4978(4) | 852(3) | 5739(3) | 47(1) |
| C(9) | 5826(4) | 38(3) | 6138(4) | 59(1) |
| C(10) | 7153(5) | -133(4) | 5821(5) | 82(2) |
| C(11) | 7609(6) | 489(6) | 5102(5) | 95(3) |
| C(12) | 6761(6) | 1287(5) | 4694(4) | 90(3) |
| C(13) | 5436(5) | 1483(4) | 4999(4) | 66(2) |
| C(14) | 1066(5) | 3080(4) | 6855(5) | 73(2) |
| C(15) | 6568(4) | 1558(3) | 8634(3) | 46(1) |
| C(16) | 7838(4) | 1571(3) | 8186(4) | 62(2) |
| C(17) | 8933(4) | 855(4) | 8464(5) | 79(2) |
| C(18) | 8808(5) | 104(4) | 9172(5) | 79(2) |
| C(19) | 7583(5) | 73(4) | 9634(4) | 74(2) |

| | | | | |
|---|---|---|---|---|
| C(20) | 6497(4) | 786(3) | 9377(3) | 57(1) |
| C(21) | 4236(4) | 2473(3) | 9620(3) | 45(1) |
| C(22) | 2942(5) | 1960(4) | 9583(3) | 67(2) |
| C(23) | 2416(6) | 1890(4) | 10603(4) | 78(2) |
| C(24) | 3230(5) | 2328(4) | 11685(4) | 69(2) |
| C(25) | 4559(5) | 2826(3) | 11767(4) | 68(2) |
| C(26) | 5063(5) | 2903(3) | 10759(3) | 57(1) |
| C(27) | 5840(5) | 3700(3) | 8066(4) | 60(2) |
| C(28) | 7445(6) | 3871(4) | 9093(5) | 86(2) |
| C(29) | 6061(5) | 3787(3) | 6791(4) | 72(2) |
| C(30) | 4752(7) | 4494(3) | 8179(5) | 81(2) |

TABLE 2

Fractional atomic co-ordinates ($x10^4$) for *Trans*-**18**

| | x | y | z |
|---|---|---|---|
| Si(1) | 5005(1) | 2493 | 8270(1) |
| P(1) | 3280(1) | 1093(1) | 6210(1) |
| B(1) | 2609(6) | 28(3) | 6947(5) |
| N(1) | 3477(3) | 2163(2) | 6889(2) |
| C(1) | 1771(4) | 1473(3) | 4823(3) |
| C(2) | 1030(4) | 952(4) | 3740(3) |
| C(3) | -112(5) | 1379(5) | 2792(4) |
| C(4) | -532(5) | 2300(5) | 2895(4) |
| C(5) | 177(4) | 2810(3) | 3967(4) |
| C(6) | 1357(4) | 2388(3) | 4943(3) |
| C(7) | 2211(4) | 2833(3) | 6180(4) |

| | | | |
|---|---|---|---|
| C(8) | 4978(4) | 852(3) | 5739(3) |
| C(9) | 5826(4) | 38(3) | 6138(4) |
| C(10) | 7153(5) | -133(4) | 5821(5) |
| C(11) | 7609(6) | 489(6) | 5102(5) |
| C(12) | 6761(6) | 1287(5) | 4694(4) |
| C(13) | 5436(5) | 1483(4) | 4999(4) |
| C(14) | 1066(5) | 3080(4) | 6855(5) |
| C(15) | 6568(4) | 1558(3) | 8634(3) |
| C(16) | 7838(4) | 1571(3) | 8186(4) |
| C(17) | 8933(4) | 855(4) | 8464(5) |
| C(18) | 8808(5) | 104(4) | 9172(5) |
| C(19) | 7583(5) | 73(4) | 9634(4) |
| C(20) | 6497(4) | 786(3) | 9377(3) |
| C(21) | 4236(4) | 2473(3) | 9620(3) |
| C(22) | 2942(5) | 1960(4) | 9583(3) |
| C(23) | 2416(6) | 1890(4) | 10603(4) |
| C(24) | 3230(5) | 2328(4) | 11685(4) |
| C(25) | 4559(5) | 2826(3) | 11767(4) |
| C(26) | 5063(5) | 2903(3) | 10759(3) |
| C(27) | 5840(5) | 3700(3) | 8066(4) |
| C(28) | 7445(6) | 3871(4) | 9093(5) |
| C(29) | 6061(5) | 3787(3) | 6791(4) |
| C(30) | 4752(7) | 4494(3) | 8179(5) |

TABLE 3

Anisotropic temperature factors (Å x$10^3$) for *Trans*-**18**

| | U11 | U22 | U33 | U23 | U13 | U12 |
|---|---|---|---|---|---|---|
| Si(1) | 40 | 41 | 39 | -3 | 12 | -9 |
| P(1) | 32 | 39 | 39 | -2 | 12 | -2 |
| B(1) | 56(2) | 43(2) | 68(3) | 3(2) | 27(2) | -9(2) |
| N(1) | 39(1) | 38(1) | 41(1) | -2(1) | 13(1) | 1(1) |
| C(1) | 32(2) | 58(2) | 43(2) | 0(2) | 10(1) | -5(1) |
| C(2) | 49(2) | 91(3) | 49(2) | -16(2) | 13(2) | -14(2) |
| C(3) | 49(2) | 140(5) | 45(2) | -12(3) | 1(2) | -18(3) |
| C(4) | 42(2) | 138(5) | 58(3) | 30(3) | -3(2) | -2(3) |
| C(5) | 41(2) | 78(3) | 76(3) | 28(2) | 12(2) | 3(2) |
| C(6) | 32(2) | 56(2) | 51(2) | 9(2) | 12(1) | -1(2) |
| C(7) | 44(2) | 38(2) | 65(2) | 8(2) | 16(2) | 4(1) |
| C(8) | 35(2) | 62(2) | 42(2) | -14(2) | 11(1) | -1(2) |
| C(9) | 47(2) | 64(2) | 63(2) | -20(2) | 13(2) | 7(2) |
| C(10) | 54(2) | 100(4) | 87(3) | -38(3) | 17(2) | 19(3) |
| C(11) | 50(3) | 160(6) | 82(3) | -39(4) | 30(2) | 11(3) |
| C(12) | 66(3) | 147(6) | 72(3) | 1(3) | 41(2) | -18(3) |
| C(13) | 55(2) | 93(3) | 56(2) | 3(2) | 26(2) | -5(2) |
| C(14) | 62(2) | 72(3) | 89(3) | -5(2) | 31(2) | 20(2) |
| C(15) | 37(2) | 58(2) | 36(2) | -4(1) | 4(1) | -3(2) |
| C(16) | 40(2) | 80(3) | 65(2) | -8(2) | 15(2) | -7(2) |
| C(17) | 36(2) | 112(4) | 81(3) | -24(3) | 9(2) | -1(2) |
| C(18) | 49(2) | 92(3) | 77(3) | -9(3) | -5(2) | 24(2) |
| C(19) | 69(3) | 78(3) | 63(2) | 9(2) | 6(2) | 19(2) |
| C(20) | 51(2) | 67(2) | 49(2) | 5(2) | 12(2) | 1(2) |

| | | | | | | |
|---|---|---|---|---|---|---|
| C(21) | 49(2) | 43(2) | 42(2) | -4(2) | 14(1) | 0(2) |
| C(22) | 67(2) | 91(3) | 46(2) | -14(2) | 21(2) | -30(2) |
| C(23) | 75(3) | 110(4) | 57(2) | -13(3) | 34(2) | -36(3) |
| C(24) | 80(3) | 88(3) | 46(2) | 0(2) | 28(2) | -3(3) |
| C(25) | 80(3) | 77(3) | 43(2) | -12(2) | 16(2) | -7(2) |
| C(26) | 63(2) | 59(2) | 46(2) | -5(2) | 12(2) | -7(2) |
| C(27) | 63(2) | 58(2) | 59(2) | -1(2) | 20(2) | -23(2) |
| C(28) | 82(3) | 82(3) | 83(3) | -9(3) | 13(3) | -48(3) |
| C(29) | 73(3) | 69(3) | 77(3) | 10(2) | 28(2) | -25(2) |
| C(30) | 114(4) | 40(2) | 91(3) | -9(2) | 36(3) | -20(2) |

The temperature factor exponent takes the form:

$-2\ (U\ .h\ .a^* + \ldots + 2U\ .h.k.a^*.b^*)$

TABLE 4

Hydrogen fractional atomic co-ordinates ($x10^4$) and isotropic temperature factors ($Å^2$ $x10^3$) for *Trans*-**18**

| | x | y | z | U |
|---|---|---|---|---|
| H(1) | 2432(58) | -474(29) | 6252(35) | 86(2) |
| H(2) | 3442(42) | -107(35) | 7817(25) | 86(2) |
| H(3) | 1551(35) | 252(36) | 7052(43) | 86(2) |
| H(21) | 1321(4) | 311(4) | 3669(3) | 86(2) |
| H(31) | -631(5) | 1035(5) | 2043(4) | 86(2) |
| H(41) | -1329(5) | 2592(5) | 2212(4) | 86(2) |
| H(51) | -138(4) | 3446(3) | 4038(4) | 86(2) |
| H(71) | 2691(4) | 3418(3) | 6085(4) | 86(2) |
| H(91) | 5498(4) | -409(3) | 6633(4) | 86(2) |
| H(101) | 7757(5) | -695(4) | 6110(5) | 86(2) |

| | | | | |
|---|---|---|---|---|
| H(111) | 8529(6) | 366(6) | 4883(5) | 86(2) |
| H(12) | 7090(6) | 1721(5) | 4185(4) | 86(2) |
| H(131) | 4842(5) | 2047(4) | 4704(4) | 86(2) |
| H(141) | 1629(5) | 3363(4) | 7641(5) | 86(2) |
| H(142) | 553(5) | 2518(4) | 6988(5) | 86(2) |
| H(143) | 292(5) | 3513(4) | 6361(5) | 86(2) |
| H(161) | 7948(4) | 2087(3) | 7678(4) | 86(2) |
| H(171) | 9798(4) | 885(4) | 8153(5) | 86(2) |
| H(181) | 9567(5) | -395(4) | 9346(5) | 86(2) |
| H(191) | 7487(5) | -450(4) | 10138(4) | 86(2) |
| H(201) | 5658(4) | 755(3) | 9717(3) | 86(2) |
| H(221) | 2372(5) | 1634(4) | 8831(3) | 86(2) |
| H(231) | 1485(6) | 1536(4) | 10538(4) | 86(2) |
| H(241) | 2874(5) | 2288(4) | 12388(4) | 86(2) |
| H(251) | 5147(5) | 3125(3) | 12536(4) | 86(2) |
| H(261) | 5996(5) | 3258(3) | 10835(3) | 86(2) |
| H(281) | 8171(6) | 3387(4) | 9057(5) | 86(2) |
| H(282) | 7310(6) | 3860(4) | 9892(5) | 86(2) |
| H(283) | 7852(6) | 4473(4) | 8966(5) | 86(2) |
| H(291) | 6742(5) | 3294(3) | 6700(4) | 86(2) |
| H(292) | 6521(5) | 4386(3) | 6733(4) | 86(2) |
| H(293) | 5057(5) | 3735(3) | 6146(4) | 86(2) |
| H(301) | 3736(7) | 4416(3) | 7556(5) | 86(2) |
| H(302) | 5190(7) | 5088(3) | 8063(5) | 86(2) |
| H(303) | 4648(7) | 4475(3) | 8988(5) | 86(2) |

TABLE 5

Bond lengths (Å) for *Trans*-**18**

| | | | |
|---|---|---|---|
| N(1)-Si(1) | 1.775(5) | C(15)-Si(1) | 1.880(6) |
| C(21)-Si(1) | 1.889(5) | C(27)-Si(1) | 1.919(6) |
| B(1)-P(1) | 1.925(6) | N(1)-P(1) | 1.690(5) |
| C(1)-P(1) | 1.791(5) | C(8)-P(1) | 1.816(5) |
| C(7)-N(1) | 1.500(6) | C(2)-C(1) | 1.404(6) |
| C(6)-C(1) | 1.373(6) | C(3)-C(2) | 1.361(8) |
| C(4)-C(3) | 1.379(9) | C(5)-C(4) | 1.381(8) |
| C(6)-C(5) | 1.393(6) | C(7)-C(6) | 1.503(7) |
| C(14)-C(7) | 1.522(7) | C(9)-C(8) | 1.378(6) |
| C(13)-C(8) | 1.387(7) | C(10)-C(9) | 1.383(7) |
| C(11)-C(10) | 1.360(10) | C(12)-C(11) | 1.359(9) |
| C(13)-C(12) | 1.380(7) | C(16)-C(15) | 1.401(6) |
| C(20)-C(15) | 1.402(6) | C(17)-C(16) | 1.379(8) |
| C(18)-C(17) | 1.367(9) | C(19)-C(18) | 1.374(8) |
| C(20)-C(19) | 1.372(7) | C(22)-C(21) | 1.365(6) |
| C(26)-C(21) | 1.404(6) | C(23)-C(22) | 1.399(6) |
| C(24)-C(23) | 1.358(7) | C(25)-C(24) | 1.368(7) |
| C(26)-C(25) | 1.375(7) | C(28)-C(27) | 1.547(8) |
| C(29)-C(27) | 1.537(8) | C(30)-C(27) | 1.529(9) |

TABLE 6

Bond angles (°) for *Trans*-**18**

| | | | |
|---|---|---|---|
| C(15)-Si(1)-N(1) | 108.1(2) | C(21)-Si(1)-N(1) | 109.4(2) |
| C(21)-Si(1)-C(15) | 105.2(3) | C(27)-Si(1)-N(1) | 110.4(3) |
| C(27)-Si(1)-C(15) | 111.3(3) | C(27)-Si(1)-C(21) | 112.2(3) |

| | | | |
|---|---|---|---|
| N(1)-P(1)-B(1) | 120.5(3) | C(1)-P(1)-B(1) | 111.5(3) |
| C(1)-P(1)-N(1) | 93.8(3) | C(8)-P(1)-B(1) | 113.6(3) |
| C(8)-P(1)-N(1) | 109.6(2) | C(8)-P(1)-C(1) | 105.2(3) |
| P(1)-N(1)-Si(1) | 125.3(3) | C(7)-N(1)-Si(1) | 122.4(3) |
| C(7)-N(1)-P(1) | 112.3(3) | C(2)-C(1)-P(1) | 128.1(4) |
| C(6)-C(1)-P(1) | 110.5(4) | C(6)-C(1)-C(2) | 121.4(5) |
| C(3)-C(2)-C(1) | 118.5(6) | C(4)-C(3)-C(2) | 120.7(5) |
| C(5)-C(4)-C(3) | 121.0(5) | C(6)-C(5)-C(4) | 119.1(5) |
| C(5)-C(6)-C(1) | 119.3(5) | C(7)-C(6)-C(1) | 114.9(4) |
| C(7)-C(6)-C(5) | 125.7(5) | C(6)-C(7)-N(1) | 107.3(4) |
| C(14)-C(7)-N(1) | 113.3(4) | C(14)-C(7)-C(6) | 110.5(4) |
| C(9)-C(8)-P(1) | 119.3(4) | C(13)-C(8)-P(1) | 120.7(4) |
| C(13)-C(8)-C(9) | 120.0(4) | C(10)-C(9)-C(8) | 119.6(6) |
| C(11)-C(10)-C(9) | 120.4(6) | C(12)-C(11)-C(10) | 120.1(5) |
| C(13)-C(12)-C(11) | 121.1(6) | C(12)-C(13)-C(8) | 118.8(6) |
| C(16)-C(15)-Si(1) | 123.6(4) | C(20)-C(15)-Si(1) | 120.3(4) |
| C(20)-C(15)-C(16) | 116.0(5) | C(17)-C(16)-C(15) | 121.1(5) |
| C(18)-C(17)-C(16) | 121.2(5) | C(19)-C(18)-C(17) | 119.2(5) |
| C(20)-C(19)-C(18) | 120.1(6) | C(19)-C(20)-C(15) | 122.3(5) |
| C(22)-C(21)-Si(1) | 121.7(4) | C(26)-C(21)-Si(1) | 121.5(4) |
| C(26)-C(21)-C(22) | 116.4(4) | C(23)-C(22)-C(21) | 122.4(5) |
| C(24)-C(23)-C(22) | 119.6(5) | C(25)-C(24)-C(23) | 119.6(5) |
| C(26)-C(25)-C(24) | 120.7(5) | C(25)-C(26)-C(21) | 121.2(5) |
| C(28)-C(27)-Si(1) | 110.8(4) | C(29)-C(27)-Si(1) | 111.5(4) |
| C(29)-C(27)-C(28) | 108.7(5) | C(30)-C(27)-Si(1) | 111.2(4) |
| C(30)-C(27)-C(28) | 106.5(5) | C(30)-C(27)-C(29) | 108.1(5) |

TABLE 7

Selected non-bonded distances (Å) for *Trans*-**18**

Intramolecular:

| | | | |
|---|---|---|---|
| P(1)-Si(1) | 3.077 | C(7)-Si(1) | 2.873 |